The colour measurement of ceramic samples using a commercial colour measuring device and a laboratory spectrophotometer

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DECLARATION

I hereby declare that this thesis describes my own work, is of my own composition and has not been submitted as part of any other higher degree.

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ABSTRACT

The selection of shade for a porcelain crown is a subjective process and mode of fabrication is known to have an effect.

This investigation sought to determine the accuracy of a commercially-available shade-matching device (*IdentaColor II*) when used to measure the colour of proprietary, custom-made all-ceramic and custom-made metal-ceramic samples of shades B1, A3 and D4 under different calibration and lighting conditions as well as over time. The findings from the first part of the study led to an investigation of the influence of fabrication technique on the colour co-ordinates recorded for the ceramic samples measured previously. Colour measurements were made using a laboratory spectrophotometer, *Spectraflash SF600* and were used as a comparator for the *IdentaColor II*. The reproducibility of these colour measurements was also assessed. The fabrication variables investigated were shade, thickness of ceramic, type of ceramic sample, number of firing cycles, operator, and method of condensation. An attempt was made to determine the correlation between fabrication technique, porosity and colour co-ordinates.

The results indicated that *IdentaColor II* used a measurement system for colour values that conformed to no known standard which made validation difficult. Differences in the colour values were found between different calibration and lighting conditions and over time but these differences were clinically inconsequential. The results from *IdentaColor II* were reproducible but with limitations: the colours recorded were generally lighter than the chosen standard, there was a preponderance of “A” shades and the device never recorded the intended shade of a sample. The limitations of the colour scale used by *IdentaColor II* made its further investigation difficult and comparisons with colour-reference standards impossible. The results for the samples which had been measured by *IdentaColor II* and

Spectraflash SF600 were different: (1) the colour scales used by the two devices were different, (2) the scale used by IdentaColor II had a larger range, (3) the measurements from *Spectraflash SF600* were more consistent both within each data set and over time and (4) the trends in the recorded colour co-ordinates when the ceramic thickness increased were different. The colour co-ordinates (C.I.E. L*a*b*) from *Spectraflash SF600* for samples ostensibly of the same shade of ceramic were affected by the mode of fabrication which in turn influenced porosity. The colour co-ordinates generally decreased as the ceramic thickness of metal-ceramic samples of shades B1, A3 and D4 increased and as the amount of pre-sintered slurry condensation increased of metal-ceramic tabs of shades B1 and A3. Metal-ceramic tabs were a closer colour match to the shade tabs than all-ceramic samples of the same thickness.

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GLOSSARY OF TERMS

C.I.E - (Commission Internationale d'Eclairage [International Commission on Illumination])

CV - Coefficients of Variation %

D_{65} – C.I.E. standard illuminant D with a colour temperature of 6500K

SD - Standard Deviation

α – the colour value from IdentaColor II thought to represent its lightness dimension

β - the colour value from IdentaColor II thought to represent its red-green axis

γ - the colour value from IdentaColor II thought to represent its yellow-blue axis

L* - the lightness dimension of the C.I.E. L*a*b* colour space

a* - the red-green axis of the C.I.E. L*a*b* colour space

b* - the yellow-blue axis of the C.I.E. L*a*b* colour space

Δe*:* The mean of each data set was calculated and then the colour difference between each individual reading and this mean was calculated (Δe), using the colour values from IdentaColor II

ΔE: Colour differences calculated using the C.I.E.DE 2000 equation with colour values from IdentaColor II

ΔE_{00}: Colour differences calculated using the C.I.E.DE 2000 equation with the colour co-ordinates from Spectraflash SF600

CHAPTER 1: INTRODUCTION

One of the main driving forces in dentistry today is the need to provide restorations that match the colour of the existing dentition. However, selecting the correct shade and fabricating a restoration to match this colour is subjective and therefore varies between individuals.

Correctly recording the dimensions of the colour needed for a restoration and communicating these to the laboratory technician is complex. The shade can be assessed by humans or measured by instrumental shade-taking devices. However, it can be difficult to identify subtle differences in colour and the accuracy of human shade selections can be influenced by many factors. Instrumental devices are increasingly being investigated in the literature, although problems relating to their precision and repeatability under different test conditions are evident.

Ceramics have been used in dentistry since the 18th century in an attempt to mimic the shade, translucency and opacity of the natural tooth. The mode of fabrication can be manipulated to allow the correct shape and colour of restoration to be constructed. These materials have to be able to withstand the forces generated in function and maintain their aesthetics while being biocompatible within the oral environment. The effect of the different stages in the fabrication of feldspathic ceramic restorations on the final shade of the restoration has to be known to ensure accurate shade reproduction.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

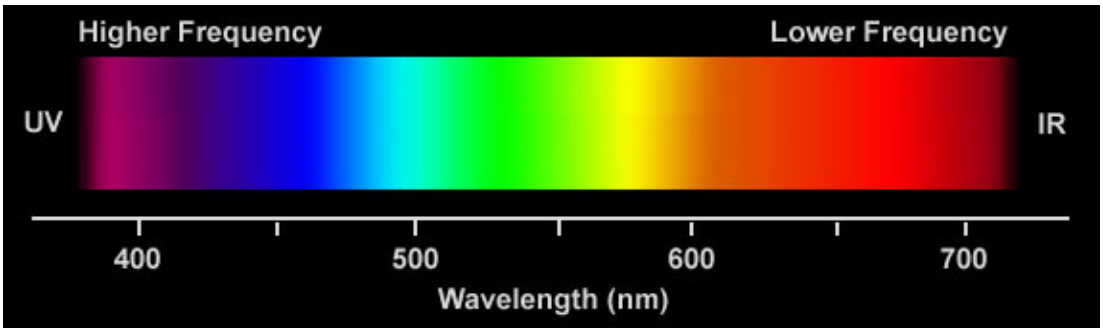
The literature review was designed to describe the subject areas in depth and outline previous studies and their conclusions. There were several difficulties in evaluating the colour of a laboratory-made restoration:

- The problems of colour measurement of ceramic samples are discussed in section 2.4. In addition, considerable variability was found in the dental literature as to the colour-difference values that equated to acceptable and perceptible differences when assessing dental materials (section 2.3.2.3)
- The factors affecting the fabrication of ceramic restorations/samples are discussed in section 2.5

2.2 Light

Visible light is a small part of the electromagnetic (EM) spectrum. All EM radiation consists of small packets of energy, termed photons, and waves of energy that interact with matter in a variety of ways. Visible light often takes the form of polychromatic light which is composed of electromagnetic radiation of more than one wavelength, for example, when a beam of visible white light is passed through a glass prism a series of coloured bands is produced, ranging from violet to red. These colours and their wavelengths are shown in Figure 2.1.

Figure 2.1. Visible Colour Spectrum



Source: http://www.wikipedia.org/

2.2.1 Light sources

The lighting conditions under which the object is viewed will have an effect on its colour. Saleski (1972), using his personal experience from the colour viewing industry, stated that the dental light source should have four properties: 1. contain the complete colour content, 2. be intense enough to overcome the ambient light but not so intense that colours become washed out, 3. be comfortable to the eye so as it allow it to perceive colour accurately and 4. be standard in that it does not change from day to day, place to place or season to season. These principles are scientifically sound, however, there has been little evaluation of them in the dental literature.

Results of investigations (Culpepper 1970, Donahue et al 1991, Lee et al 2004, Dagg et al 2004 and Lee and Powers 2005b) concluded that the light source has an effect on the colour-matching abilities of human observers and on the colour co-ordinates recorded by instrumental devices. Teeth and ceramic are viewed under a variety of light sources which will affect the colour observed.

2.2.2 Consistency of the Light Source

The following studies supported Saleski's 4th critera:

Lee et al (2004) assessed the effect of standard C.I.E. illuminants (A, C and D_{65}) on the 1976 C.I.E. L*a*b* co-ordinates of shade tabs. There were colour differences between different light sources when measuring Vita Vitapan ® Classical (Vita-Zahnfabrik®, Bad Säckingen, Germany) shade guide tabs. The authors concluded that these differences were not visually perceptible; however, the ΔE_{ab} value considered visually perceptible was ≥3.3. This figure has not been universally agreed (section 2.3.2.3). If these results were evaluated using a different colour difference threshold, for example Seghi et al (1989a), then differences would have been clinically perceptible as all were ≥1 ΔE_{ab} unit between the tabs when viewed under light sources A and C.

Lee and Powers (2005b) compared different standard illuminants on the spectral curves of seven restorative materials. The mean colour difference (ΔE_{ab}) between standard illuminants A and D_{65} was 1.92 (±0.62) units which was within the range of colour differences found by Lee et al (2004).

Dagg et al (2004) found a significant difference between novice and experienced personnel when shade matching 54 ceramic tabs under a standard and constant light source. However, under window daylight and fluorescent tube lighting there was no significant difference between the two observer's groups. Indicating that altering the light source affects human observers, to varying degrees, as well as instrumental devices.

2.2.3 Environmental Surroundings

Natural light is not uniform in its wavelengths throughout the world. Burkinshaw (2004) stated light entering dental surgeries/laboratories has already been altered by scattering and absorption in the earth's atmosphere. In addition, the latitude of the surgery, the time of year, the weather conditions and the time of day all affect the nature of the light. Saleski (1972) stated that the colour temperature of light can vary from 1000 Kelvins to over 20,000 Kelvins depending on the time of day and that the intensity can vary from 100 and 10,000 foot-candles depending on weather conditions. This variability of natural daylight suggested that it was not an ideal light source for dental colour matching. Daylight therefore does not fulfil the criteria stated by Saleski (1972) for a light source. It was therefore essential that more objective methods of colour assessment were used. However, the effect of these differences in light on dentally relevant samples has never been assessed.

2.2.4 Light and its Interactions with Ceramic

The basic structure and composition of ceramic will have an influence on the way light interacts with them. All dental ceramics contain small crystals which are embedded in a matrix. The relative amount of crystals (usually leucite or alumino-silicate or a combination of both) and glass is dependant on the manufacturer. The crystal size and composition, pore size and number, presence of voids or cracks, the matrix, as well as the constituent's physical properties, contribute to the overall colour of the ceramic. The definitions are sourced from www.color-tec.com.

Reflection is defined as "the process by which radiant energy is returned from a material or object". If the photon is returned at an angle that is equal to the angle at

which they strike the surface, this is termed specular reflection. The ceramic crystals will reflect the majority of photons that strike them. The surface area to volume ratio of the crystals is important in determining the amount of reflection. In addition, the surface finish of ceramic has a bearing on the amount of reflection. The amount of reflected light helps to determine the brightness of a tooth or ceramic, the more photons that will be reflected the brighter these materials will appear.

Scattering can again return electromagnetic radiation toward its source as it is defined as the “redirection of radiant energy”. The radiation is dispersed in varying directions from the surface and within the entity. Scattering therefore reduced the intensity of the radiation being returned from ceramic. The size and distribution of ceramic particles affect scatter patterns.

Absorption is the *decrease in directional transmittance of light, resulting in a modification or conversion of the absorbed energy*. Energy that is absorbed does not emerge from the material and is converted to another form of EM radiation. Ceramics absorb photons depending on the particle size of the material, the metal oxides present and the presence of pores in the ceramic.

Refraction is defined as the “change in the direction of light determined by change in the velocity of the light in passing from one medium to another”. Refraction in ceramic tends to be more uniform than in teeth as it is more homogenous if standardised sintering procedures are followed. However, variation in the amount of fusion and the pore size allows refraction to occur.

Transmission is the process whereby “radiant energy passes through a material”. Dental restorations contain metal oxides and opacifiers as well as opaque copings.

These can block the transmission of light through dental ceramic, altering its appearance.

Metamerism is the *property of two specimens that match under a specified illuminant and may appear to be a miss match under a second specified illuminant*. There has been limited research studying the effects of metamerism in dentistry, although the metameric effects in colour matching in the textile industry are well documented. Metamerism was thought to produce problems in dental shade matching (Vanini and Mangani 2001) and this was explained by Lee and Powers (2005c) as human dentine exhibited metameric effects. However, no literature was available that illustrated metamerism in dental ceramics and only limited evidence was found for resin composites (Lee and Powers 2005b).

Opalescence and fluorescence can also occur and different metal oxides can be used to recreate these effects.

2.3 Colour Models and Colour Differences

Colour cannot exist without light. The object observed modifies the light that strikes it and then the observer's eyes or a measuring device captures the reflected portion of the light. If the light, object or observer is changed then the perception of the colour of the object will be altered.

It is thought that humans can perceive around eight million colours (Burkinshaw 2004). There are numerous scales used to place colours into an orderly arrangement and to enable communication between individuals about one particular colour. These scales are used to describe the distinct properties of colour as they are perceived by

the author or committee that constructed them. Albert Munsell's colour order system and the model recommended by C.I.E. in 1978 (Commission Internationale d'Eclairage [International Commission on Illumination]) were the most common in the dental literature:

2.3.1 Munsell's Colour Order System

Albert Munsell described colour as having three attributes:

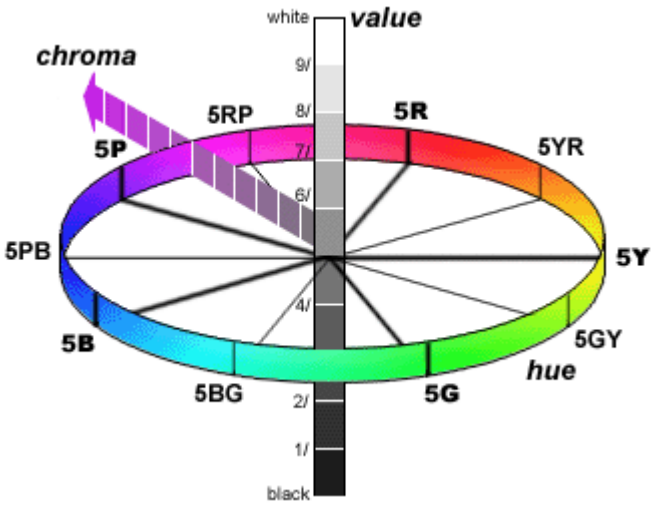
(a) Hue: The quality by which we distinguish one colour family from another, as red from yellow, or green from blue or purple.

(b) Value: The quality by which we distinguish a light colour from a dark one.

(c) Chroma: The quality of colour by which we distinguish a strong colour from a weak one.

The Munsell Colour System was published in 1915. It was based on steps of equal visual perception with any colour being defined as a point within the three-dimensional Munsell colour space. The system's attributes are Munsell Hue (H), Munsell Chroma (C) and Munsell Value (V) which correspond to perceived hue, chroma and lightness respectively (Figure 2.2).

Figure 2.2. Framework of Munsell's Colour Order System



Source: http://www.wikipedia.org/

Where R = Red, Y = Yellow, G = Green, B = Blue and P = Purple

In Munsell's scales there are one hundred Hues; ten major Hues (five principals and five intermediates) each placed ten steps apart in the Hue scale on the horizontal plane from the central axis which move sequentially around the central axis (z axis). The Value symbol 0/ is used for absolute black and 10/ for absolute white. Accordingly, middle grey is designated the symbol 5/, the midpoint of the central axis (y axis). The chroma scales start at /0 and moves from the central axis radially, its limit is set by the availability of colorants. The purest colours are found at the extremes of the colour cylinder (x axis).

However, the original scale had two major problems: 1. the perceptual spacing of colours varied with their location in the colour space and 2. quantitative analysis between colours could only define changes in a single colour attribute (Value, Chroma or Hue) at any one point.

2.3.2 Commission Internationale d'Eclairage (International Commission on Illumination) C.I.E.

C.I.E formalised their colour specification in 1931. This system is based on the three primary colours, red, green and blue. It is derived from colour matching experiments and spectral response curves that produced a set of averaged results for humans with normal colour vision, under standardised conditions. The results of these experiments, which used forty-nine observers for the 1964 set of experiments, provided numerical data, which defined the average human colour receptor response to a particular light source (C.I.E. publication S 014-1/E:2006). The original data set from 1931 observed results used only a 2° field of view but the subsequent set of observer values from 1964 employed a 10° field of view. A 10° field was considered to be both more consistent, and more representative. The light sources used in these experiments were from the C.I.E.'s set of standard illuminants (A, B, C and D).

Two problems were associated with the C.I.E. specification and illuminants. One issue is that the light sources used in industry do not always exactly match the C.I.E. standard illuminants. The other problem is that the observer will not perceive colour in exactly the same manner as the standard observer, which is derived from a set of averaged results. This may account for genuine differences of opinion between observers as to the quality of a colour match, but it remains one of the most commonly used systems.

The C.I.E. never intended this specification to describe colour appearance, only to predict equality in appearance. The need for a perceptibly uniform appearance and for colour-difference equations drove the production of other C.I.E. systems, for example, the 1976 C.I.E. L*a*b* uniform colour space. This allowed the calculation of

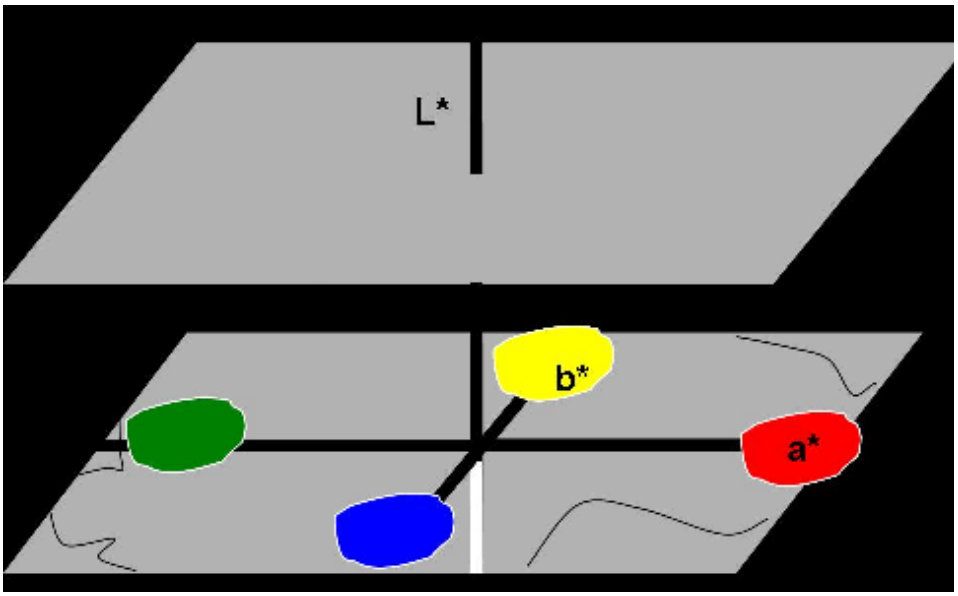
different colour-difference equations including C.I.E. L*a*b* (ΔE_{ab}) and C.I.E.DE2000 (ΔE_{00}).

2.3.2.1 1976 C.I.E. L*a*b* Uniform Colour Space

C.I.E. L*a*b* was only tentatively recommended in 1976. The 1976 C.I.E. L*a*b* colour-difference equation (ΔE_{ab}) was designed to evaluate small colour differences between materials. Two main limitations exist: it is not a uniform colour space and its original colour-difference equation (ΔE_{ab}) does not identify the relative effect of lightness, chroma and hue differences.

This colour order system (Figure 2.3) provided a useful technique for colour difference assessment. The colour of a tooth or restoration could be recorded numerically within the three–dimensional diagram which can then be compared to another reading that has been charted. The system contained three colour co-ordinates: The L* dimension, the lightness dimension corresponds to Value in the Munsell system and is based on a scale of 0 to 100, where 0 is a perfect black. However, the a* and b* co-ordinates do not correspond to elements of Munsell's Colour Order. The a* positions the colour on the red/green axis (positive a* = redness, negative a* = greenness) and the b* on the yellow/blue axis (positive b* = yellowness, negative b* = blueness). The further the co-ordinates are from 0 the more saturated the colour is. When a* and b* are considered together they provide the same information as Munsell's Hue and Chroma.

Figure 2.3. 1976 C.I.E. L*a*b* Colour Space



2.3.2.2 1976 C.I.E.L*a*b* Colour Difference Equations (ΔE_{ab} and ΔE_{00})

The 1976 C.I.E. L*a*b* colour space is used when calculations involving the colour-difference equation ΔE_{ab} were considered. Swift et al (1994) illustrated the mathematical formula in the dental literature that provided the numerical distance between two points in colour space. However, it was not a marker of how far apart the colours were visually. The colour differences in L*, a* and b* values of two samples was given by the ΔE parameter. The equation used in the calculation of ΔE_{ab} was:

$$\Delta E_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a)^2 + (\Delta b)^2}$$

There have been slight improvements to the C.I.E. equations in an effort to make them more accurate. In 2000 C.I.E. adopted a new colour-difference equation, C.I.E.DE 2000 (ΔE_{00}) which was unusual as it did not have its own colour space, it utilised the 1976 C.I.E. L*a*b* space. The ΔE_{ab} equation was predominant in the

literature, however, ΔE_{00} is now being used more frequently in the assessment of dental materials.

The full equation for calculating the ΔE_{00} (Luo and Rigg 2001), is also the C.I.E. publication 142-2001. This equation was found to have improved weighting factors for blue colours and a scaling factor for the a* co-ordinate (Luo and Rigg 2001). It was approved and adopted in the C.I.E. technical report of that time "Improvement to Industrial Colour-Difference Evaluation" (Publication C.I.E. 142-2001). Its relevance and correlation to observed human responses in relation to dental materials were evaluated by Lee and Powers (2005a). The relevance of the weighting functions was assessed in this study using composite resin. The colour differences between the different formulae tested (1976 C.I.E. L*a*b*, C.I.E.DE 2000 and DIN99) were different, although no trends were found. It was recommended by the authors that proper thresholds for perceptibility and acceptability of specific dental relevance should be investigated.

Following the literature review, it was concluded that, at present, the best fitting colour difference equation for use in dentistry is the C.I.E.DE 2000 equation, especially if the colour-differences involve hue or chroma changes in dental materials. However, as it is a relatively new equation there could be unidentified difficulties.

Human ability to discriminate colour differences

Keuhni and Marcus (1979), under the auspices of Inter-Society Color Council (ISCC), stated that a ΔE_{ab} value of one unit represented, to human observers, an

acceptable colour match in half of the cases examined when viewed under uniformly controlled conditions. This figure has been used as a reference point in many articles and textbooks when assessing colour differences. It was calculated from the evaluation of textile dyes and matte paints by sixty-three observers which were compared to measurements by a spectrophotometer. Most of the observers had experience of colour matching. Repeatability analysis of the measurements recorded by the spectrophotometer showed minimal colour differences between measurements.

Human ability to discriminate colour differences using standard illuminants

Seghi et al (1989b) found that, in all cases, the twenty-seven dental personnel (twenty-three dentists and 4 technicians) could distinguish between pigmented ceramic tabs (30) of 4 mm thickness and a reference tab when the colour-differences were ≥ 2 ΔE_{ab} units (under a colour-corrected fluorescent light source). No indication was given as to the training, if any, that the observers had completed. There was little certainty on the colour match of the ceramic samples between observers when the colour-differences were ≤1 unit. For colour differences between one and two ΔE_{ab} units, observers made few incorrect judgements of shade. No repeatability analysis of the measurements recorded by a spectrophotometer or the observers was completed.

Okubo et al (1998) asked observers to match two entire shade guides to each other under natural light at the same time of day over a two week period. While attempting to standardise the time of day is useful, as discussed previously the quality of daylight varies from day to day and so may not be ideal as a standard. The

extrapolated results gave a mean ΔE_{ab} of 1.3 units was sufficient to be recorded as a mismatch.

Douglas and Brewer (1998) fabricated sixty metal-ceramic crowns of Vita shade A3.5. The colour co-ordinates were recorded and the crowns were then paired in three groups according to the variation in L*, a* and b*. ΔE_{ab} values were calculated between each set of pairs. Twenty dentists used a D_{65} lighting booth for matching. These observers were screened for any colour-vision deficiencies but were not given any specific colour-matching training. The results showed that acceptability varied depending on the colour co-ordinates, helping to support Yap's (1998) conclusion that clinical shade acceptability was dependent on the shade. Douglas and Brewer's (1998) mean ΔE_{ab} for acceptability was 1.7 units, 1.1 units for red-varying crowns and 2.1 units for yellow-varying crowns, and 0.4 units for perceptibility of the shade match of the crowns. Repeatability analysis was completed for the examiners (ΔE_{ab} = 0.34) and the colorimeter (ΔE_{ab} = 0.4 units).

Ragain and Johnston (2000) tried to define limits of colour acceptance of composite resin in the same format as Keuhni and Marcus (1979). Four groups of 12 observers (dentists, dental auxiliaries, scientists and lay people) had to match six 1.5 mm thick composite resin tabs to a standard tab. All observers were screened for any colour-vision deficiencies and were given training as to the protocol and methods of the test. The mean replacement point was when ΔE_{ab} = 2.72 units. This was the value at which discs were judged to match by 50% of the observers. The mean ΔE_{ab} for perceptibility was 0.4 units. Again no repeatability analysis for the examiners or spectrophotometer was available.

In addition to human variation, there were several factors that affected the colour differences calculated and therefore their perceptibility or acceptability: 1. shade dependent variations, 2. sample material, 3. light source used and 4. device type and measurement set-up.

Human ability to discriminate colour differences using clinical lighting

Johnston and Kao (1989) compared the colour differences obtained from the studies using two visual scales for assessing the acceptability of direct composite resin veneers. Their results illustrated that an Alpha rating from one visual scale that means the restoration matches with regard to contour, surface finish, glaze and shade had ΔE_{ab} values of between 0.5 and 12.5 units. The Bravo rated restorations had had slight contouring problems, a surface texture discrepancy that could be polished chair-side. There was also slight variability in surface glaze or the shade when compared to adjacent teeth. These restorations had values of 1.3 to 13.1 ΔE_{ab} units giving considerable overlap with the Alpha group. The average colour difference, ΔE_{ab}, for teeth and restorations that were considered a visual match in the oral environment was 3.7 units. This paper illustrated that other factors were closely linked to the appearance of a restoration and it was unlikely to be solely colour differences that affect acceptability. No repeatability analysis was given for either measurement group.

Dancy et al (2003) correlated the ΔE_{ab} values and the clinical acceptability rating of a crown. Two examiners used a modified visual scale based on the one used by Johnston and Kao (1989) for visual assessments. No correlation was found between the colour-co-ordinates and the visual rating. Extremely large ΔE_{ab} values (up to 68

units) were recorded. As the article discussed there were many factors that affected the ΔE_{ab} values recorded and it was likely that not all the colour co-ordinates measured were accurate. This paper highlighted the difficulty in the colour measurement of teeth.

2.3.2.3 Variability in the Dental Literature regarding Colour Differences

Many articles in the dental literature stated acceptability and perceptibility figures with no references. Douglas and Przybylska (1999) and Dancy et al (2003) used ΔE_{ab} values of up to 3 as agreement for shade matches in the production of batches of crowns and for a single crown at cementation respectively. Dancy et al (2003) stated that colour differences ($\Delta E_{ab} < 2$) cannot be seen. There was no mention of how these figures were obtained and what basis was used as an acceptable shade agreement. However, they recognised there was variation in the literature. Groh et al (1992) used a limit of 2 ΔE_{ab} units when comparing ceramic and shade guides as their acceptability limit. Wee et al (2002) neatly summarised the acceptability and perceptibility levels in dental studies (Figure 2.4):

Figure 2.4. Table 2 from Wee et al (2002)

Table II. Summary of studies relevant to dental color-matching tolerance

Study	Color difference (ΔE)	Results
Color perceptibility		
Kuehni and Marcus[33]	1.0	In vitro study. 50% of observers perceived a color difference.
Seghi et al[34]	2.0	In vitro study. Porcelain specimens were correctly judged by observers 100% of the time.
Johnston and Kao[21]	3.7	In vivo study. Found average color difference between compared teeth rated as a match in the oral environment.
Color acceptability		
Ragain and Johnston[36]	2.72	In vitro study. Average 50:50 ΔE replacement rate for all subjects was found.
Ruyter et al[35]	3.3	In vitro study. 50% of observers considered the composite specimens to be unacceptable.
Johnston and Kao[21]	6.8	In vivo study. Found average color difference between compared teeth rated as a mismatch within the normal range of tooth color in the oral environment.

The table showed that the limits of perceptibility and acceptability were not known. The minimum perceptible level in an *in vitro* study was 1 ΔE_{00} unit and the minimum acceptability ΔE_{00} was 2.72 units.

2.4 Colour Measurement of Dental Materials

There are numerous methods available to assess the colour of dental materials. Electronic devices allow objective and quantitative assessment of dental samples. Human observers have been shown to be unreliable at recording the colour of samples over time (Culpepper 1970, Okubo et al 1998 and Dancy et al 2003) and influenced by dental experience (Hammad 2003 and Dagg et al 2004). There was also the possibility of colour vision deficiencies (Davison and Myslinski 1990) and shade guide (Hammad 2003) affecting the results.

2.4.1 Electronic Devices

These devices generally consist of a measuring probe that is attached to a personal computer displaying the RGB or C.I.E. values. The shade-matching systems can convert these into descriptions more commonly used in dentistry.

These instruments calculate the amount of light that is reflected and measure the reflectance values of the material by evaluating its surface. Measurements are typically taken at evenly spaced wavelengths (for example 5 nm intervals) across the visible spectrum, but this varies between manufacturers and devices. Spectrophotometers were used in many different situations and the results of the

research were often compared. This caused problems, as varying the measuring geometry (Lee et al 2004) and device type (Wang et al 2005) had an effect on the colour co-ordinates recorded. All of the papers discussed that stated their device parameters used different measuring geometries, viewing angles, standard observer functions and aperture size.

2.4.1.1 Benefits of Spectrophotometers

The theoretical benefits include that the measurements are not subject to human-based biases or to problems associated with our visual apparatus and are objective. Colour is easily quantified by these devices and therefore the colour of an object is easier to communicate between individuals. In addition, the device should not be affected by many of the previously described problems as the light source is constant.

Accuracy

Culpepper (1970), a commonly quoted study, assessed the accuracy of human observers, although the testing was completed with some methodological faults. Several studies (discussed below) have tested the colour matching accuracy of electronic devices. The electronic devices were at least as accurate as the commonly quoted figures from Culpepper 1970.

Van der Bergt et al (1990) measured the colour of teeth with a colorimeter and a spectrophotometer. Unfortunately, no quantitative data were given. However, the results suggested that both devices were accurate in some respects following comparison with their standard. They concluded that the devices were subject to

error and that technical improvements were required. It should be noted that the devices were tested in 1990 and both devices have since been improved.

Okubo et al (1998) illustrated that the colorimeter used in their study selected the correct shade 50% of the time. The experiment was designed to match one Vita shade guide to another. Problems associated with shade guides have been discussed by Sproull 1973, Sorenson and Torres 1987, Schwabacher and Goodkind 1990, O'Brien et al 1991a, Yap 1998 and Paravina et al 2002a and the 50% accuracy figure may be an under- or over-estimate of the accuracy of the device. It was conceded that the authors of the paper attempted to use two guides they perceived to be the same in an attempt to overcome some of the problems associated with shade guides.

Yap et al (1999) used the Z100 composite resin (3M Dental products, St Paul, Minnesota, USA) shade tabs as their reference material. Fifty human observers were asked to match seven shade tabs from the Z100 shade guide to a Vita Lumin shade guide. The tabs had their conventional shade designations covered. These results were transferred to 1976 C.I.E L*a*b* values. A spectrophotometer was then used to compare the tabs in the same manner. The results showed that the accuracy of the spectrophotometer was dependent on the shade tested. Only shades A1, B2 and C4 had statistically significant differences between the two methods of shade comparison ($p < 0.05$). The problems of using shade guides as standards are discussed above. However, this piece of research suggested that the accuracy of colour measurements may be shade dependent.

Paul et al (2002) used three experienced dental observers to select the shade and, in addition, a reflectance spectrophotometer adapted for clinical use to record the

shade of a tooth. In 90% of the cases (9 instances), the crown fabricated following shade analysis by the spectrophotometer was a better match than those from the human observers. However, this study had a small sample size; the number of crowns per method was 10, and there was no mention of masking of the evaluators with regard to the acceptability of the crowns, or of the criteria used in the decision to cement the restoration.

Dancy et al (2003) conducted a similar experiment with twenty crowns being fabricated after shade mapping with a spectrophotometer (Colortron II, X-Rite) and twenty crowns after shade selection by two experienced observers in collaboration. The criterion in the assessment of the crowns was based on the United States Public Health Service (U.S.P.H.S.) alpha, beta system. There were no significant differences between the method of shade selection and acceptance of the crown for cementation.

Klemetti (2006) used 19 observers to match Vita Classic shades to 4 different subjects. The shade selected by the shade-taking device (Shade Eye Ex, Shofu) matched the shade most often selected by observers in 50% of the cases. Unfortunately, it was unknown what the standard was and therefore which method was more accurate.

Due to the difficulties in producing a standard with which comparisons are made defining the accuracy of devices can be difficult. However, these devices were generally at least as useful as human observers when assessing teeth or restorations.

Repeatability

Aperture size, measuring mode and the surface finish all affect the repeatability of devices (Lee et al 2004). Unfortunately, these details are rarely stated in research in the dental literature. The Society of Dyers and Colourists (2002) stated their method to assess the short-term repeatability of a colour measuring instrument. They define repeatability as:

> *Closeness of agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement*

Repeatability is distinguished from reproducibility. Reproducibility assesses the closeness of agreement of measurements when the conditions of measurement are changed. There have been several studies that investigated the repeatability of instrumental shade measuring or matching devices (Table 1). However none have used the method decided by the Society of Dyers and Colourists (2002).

Table 1 Instrumental Device Repeatability

Author	Instrument Type	Sample Type	Sample Number	Repeatability
Goldstein + Schmitt (1993)	Intra-Oral Colorimeter	Porcelain Tabs	5	0.97 to 3.39
		Acrylic tabs	5	0.27 to 2.75
Ishikawa-Nagai et al (1994)	Non-contact spectrophotometer	Dentin Porcelain Tabs	8	ΔE is 0.22+/-0.13 over 2 visits
Douglas (1997)	Colorimeter	Central Incisor	7	ICC at least .945 over 3 visits
Okubo et al (1998)	Colorimeter	Shade Tabs	16	100% over 2 visits
Horn et al (1998)	Spectrophotometer	Central Incisor	20	Mean = 0.91
Paravina (2002)	Colorimeter	Shade Tabs	16	ΔE is 0.09+/-0.04 over 3 visits
Tung et al (2002)	Intra-Oral Colorimeter	Central Incisor	11	82% over 3 visits
Cal et al (2004)	Photographic Images	Shade Tabs	3	100% over 3 visits

The results presented in Table 1 indicated that the devices tested were repeatable. With the exception of one study (Goldstein and Schmitt 1993), they were at least 82% repeatable over time, with colour differences of less than 0.22 (±0.13) or a good repeatability coefficient independent of the object tested. The test objects in these studies were teeth, porcelain tabs and shade guide tabs which were tested by similar methods across the studies. Douglas (1997) assessed the affect of changing the operator using a device when measuring upper central incisors. The colour difference between observers for this in vivo study was small (<0.61 ΔE_{ab} units).

Goldstein and Schmitt (1993) recorded larger colour differences (up to 3.39 ΔE_{ab} units). These could have been as a result of the methodology used, actual differences or due to the older type of device used.

A wide range of human intra-rater values at colour matching was found but they are generally less than those found for instrumental methods. Culpepper (1970) indicated that two observers could duplicate their original selections of two natural teeth 22% of the time, while Horn et al (1998) showed that human observers had a range of 20% to 60% reproducibility and Okubo et al (1998) recorded means of 48% and 46% repeatability for the first and second tests respectively. However, the different shade matches were not the same in each test.

Ideally, any device would have 100% short-term repeatability. Paul et al (2002) showed in their experiments that the total error due to the measuring device and positioning was 0.48 ΔE_{ab} units. In addition, the limitations discussed below may exert an influence on the measurements.

2.4.1.2 Limitations of spectrophotometers

There are well-documented limitations to the use of spectrophotometers. In both dental and industrial texts it was recorded that they have difficulty in accurately recording materials with curved surfaces (light can escape via the side of the measuring aperture), small surface areas, translucency (the background will have an effect on the values recorded by the device) and those that are polychromatic. However, evidence in the literature to support these statements was scarce. The impact of the limitations discussed below was often given in quantitative terms as ΔE units.

Seghi et al (1989b) stated, in a systematic manner, the errors found in colour measurement devices:

1. Systematic errors
    - Inaccurate calibration
    - Inaccurate device wavelength and bandwidth
    - Fluorescence
    - Variable measuring geometries
2. Random errors
    - Background noise
    - Instrument drift
    - Polarisation
    - Sample preparation
    - Sample presentation

Berns and Peterson (1988) stated that systematic errors tended to cause errors in device accuracy and random errors caused repeatability problems. The list above is fairly exhaustive; however, edge-loss and aperture size should also be included. Edge-loss occurred when light can exit the material through its edges and escape measurement by the device. Several factors were not discussed in the dental literature (background noise, instrument drift and polarisation).

Inaccurate Calibration

Spectrophotometers are usually calibrated by measuring a reference tile supplied by the manufacturer. Goodkind and Schwabacher (1987), using a Chromascan colorimeter, stated that they needed four different devices in their study due to problems of over-heating and loss of calibration. Unfortunately, the researcher has to

identify when the calibration is wavering; however, these errors are often not identified until after a series of measurements has been completed.

Variable measuring geometries

If Specular Component Excluded (S.C.E.) rather than Specular Component Included (S.C.I.) is used, diffuse reflectance is excluded from the colour measurement. Spectrophotometers generally can measure using either mode.

Two studies, Lee et al (2002) and Lee et al (2004), assessed the effect of measuring mode on the colour co-ordinates recorded when using a D_{65} light source. Using the S.C.I. mode each component of colour (L*, a* and b*) was lower compared with the S.C.E. mode across the majority of the samples (Lee et al 2004). However, the values recorded by Lee et al (2002) had no such trend. Both these studies concluded that using S.C.E. provided larger colour differences than S.C.I. following alteration of the sample surface. This discrepancy could have been due to the different properties of the materials tested (ceramic and resin composite). It was also noted that tests were operating in a different area of colour space and that this may have influenced the results. The significance of this is not clear as results between devices are rarely compared.

The second choice related to the illumination and viewing angles. The illumination angle is the angle at which the incident light strikes the object being viewed. The viewing angle is the angle at which the reflected light is collected by the device or observer. These angles are acute and described in degrees relative to the object and the beam of incident light. Paul et al (2002 and 2004) stated that “since access to the oral cavity is limited, only the 45° (illumination)/ 0° (observation) geometry is a

suitable for clinical use". This measurement set up was used by Johnston and Kao (1989) and Douglas and Brewer (1998). However, Okubo et al (1998) used a 45° (illumination)/ 45° (observation) geometry while Seghi et al (1990) and Yap (1999) stated they used the C.I.E 1931 standard observer, a 2° field of view. The remaining studies did not state the device settings.

Thirdly, the choice of illuminant will have an effect on the colour co-ordinates. In addition, Russell et al (2000) stated that careful standardisation of measurement geometry and lighting was required, as dental samples were translucent around the measuring probe.

Sample Preparation

It was difficult to assess the effect of surface type on colour measurements as most surface changes will affect the colour of the sample. Yap et al (1999) stated that absolute colour measurements were affected by curved surfaces and colour gradations.

Obregon et al (1981) recorded that the surface finish, either smooth or rough, had an effect on the Hue, Value and Chroma. They tested 1 and 2 mm thick metal-ceramic samples (shades A3 and B1) and found that the finish did not affect the Hue of the thicker samples. However, smooth, thinner samples showed a shift away from the yellow-red area. Value decreased if the smoothed surfaces were compared to rough ones. No definite conclusions could be drawn on the effect of surface finish on the Chroma values.

Kim et al (2003) and Lee et al (2004) assessed the effect of surface finishing on the colour of ceramic and resin composite respectively. Kim et al (2003) found that L* decreased whilst a* and b* values increased when glazed samples were compared to the polished ones. No analyses of the different components of the colour differences were completed; therefore the source of the colour differences could not be identified. The results of the study by Lee et al (2004) indicated that the L*a*b* values increased when composite was polished when a 3 mm aperture was used.

Sample Presentation

Spectrophotometers may be bulky and difficult to use in the clinical setting as well as having awkward probe dimensions, according to Li (2003). He also stated that correct approximation and contact of the measuring probe to dental samples (teeth) can be difficult. In addition, it has been intimated that small variations in a* and b* were as result of L* changes, i.e. samples changed colour when only the lightness of the samples changed. Tung et al (2002) stated that the equipment was expensive and that adapting spectrophotometers for use in the oral cavity was difficult.

Douglas (1997), Horn et al (1998), Okubo et al (1998), Li (2003), Paul et al (2004) and Shimada et al (2004) provided methods to reliably measure the same point on a tooth using a custom jig. The technique usually involved directing the measuring probe to the middle third of the labial surface in the centre of the test specimen and holding it in position via a custom jig. Jigs were most often used during *in vitro* studies due to their size, problems with cross-infection and cost when used in the oral environment (Douglas 1997 and Li 2003). However, some studies (Okubo 1998 and Shimada et al 2004) used a jig which could be detached and sterilised. Ishikawa-Nagai et al (1994) described the use of a non-contact spectrophotometer

which may reduce cross-infection concerns but there has been no further assessment in the dental literature. Digital cameras can be used to assess the colour, however, they have their individual problems related to flash and monitor type, and problems identifying a standard.

Edge-loss

An inherent problem with spectrophotometers is edge-loss. Edge-losses were defined by Johnston et al (1996) as the losses that occur during reflectance measurements when light is scattered within a sample beyond that part of the surface exposed to the observation system of the optical device. The amount of light lost was dependent on the scattering and absorption properties of the sample (Bolt et al 1994). The problem is confounded in dentistry as the aperture diameter has to be smaller than other industries.

Bolt et al (1994) concluded from their experiments that edge-loss was wavelength dependent and caused lower 1976 C.I.E.L*a*b* values to be recorded. They found that edge-loss changes in 1976 C.I.E.L*a*b* values were decreased by a factor of 0.7 by increasing the viewing aperture size from 4 to 5 mm. This may account for the consistently lower co-ordinates recorded using the smaller aperture (Lee et al 2004).

Johnston et al (1996) found that edge-losses were dependent on sample thickness, background and beam size. Edge-losses increased with more translucent samples and larger illumination beam sizes. A white background also increased the amount of edge-loss compared with a dark background. Dental samples often have translucency and were subject to edge-losses. It is outwith the scope of this thesis to examine these and their influence.

Aperture Size

Bolt et al (1994) used three different-sized apertures to determine the effect of edge-loss. They found that colour co-ordinates were different when different apertures were used. The colour difference values extrapolated from their results were 2.53 ΔE_{00} units between the 3 and 4 mm, 8.18 ΔE_{00} units between the 3 and 5 mm and 5.66 ΔE_{00} units between the 4 and 5 mm apertures with the colour co-ordinates being higher when a larger aperture was used.

Lee et al (2004) corroborated Bolt et al's conclusions. Measurement of several composites of one shade with an 8 mm and a 3 mm aperture was completed. The results gave a range of ΔE_{ab} values (16.23 to 27.87) between measurements of the same tab with a different aperture size.

In conclusion, the effect of aperture size merits consideration in any colour measurement experiments and when comparing data between different researchers. Measurements with a smaller aperture were consistently lower than those with a larger one.

Device type

A range of colour co-ordinates was found for samples that were supposed to be similar. Experimental, batch and fabrication variables would have had an effect on the measurements, however, another source of error was identified by Wang et al (2005). Different devices measuring the same samples (dental ceramic) produced actual and statistical differences in colour measurement. The devices used the same

illuminant (D_{65}) and measuring geometry (2° standard observer). There was a linear relationship between the co-ordinates recorded by the five devices. The ranges of errors were: 1. L* - 0.5 to 1.6 units, 2. a* - 0.07 to 0.23 units and 3. b* - 0.15 to 0.69 units.

The magnitudes of these errors make comparison of results from different studies difficult as they would impinge on the validity of cross-research comparisons. In addition, several factors stated by Seghi et al (1989b) were not discussed in the dental literature and may have influenced the readings (background noise, instrument drift, polarisation).

2.5 Ceramics and Ceramic Fabrication Variables

A variety of different dental ceramics is available and the terminology and classification not easily standardised. Terms are often used interchangeably which results in further confusion in the dental literature. The composition of dental ceramics varied between manufacturers and ceramics used for different purposes, for example opaque or dentine (body) ceramics.

The manufacturing and firing processes can be adjusted to influence the physical properties of the ceramic created. Some manufacturers add organic dyes to the powder to aid identification of the different types of ceramic which are burned off during the firing process.

Many factors (different manufacturers and variables in the fabrication process) make small differences to the final colour of ceramic which are often individually considered to be insignificant and are discussed below. However, these factors in

combination may exert an influence that alters the ceramic colour to a detectable level.

2.5.1 Effect of Metal Type and Surface on the Colour of Ceramic

The effect of the metal alloy composition on the colour co-ordinates of specimens had an affect on the colour of the ceramic produced. Research papers in the following section that assessed this topic were spread over twenty years with little standardisation amongst them. In addition, several pieces of research only used human observers to distinguish between samples of slightly different colours. The colour changes were dependent on:

- The metal alloy
- The thickness and manufacturer of the opaque porcelain
- The thickness and manufacturer of the dentine ceramic

The only exception was Barghi and Richardson (1978) who found that metal alloy type had no effect on the final colour of ceramic. The effect of the metal is considered relative to other metals tested and not the intended colour of the ceramic, as only one study (Koutayas et al 2003) used controls (all-ceramic core samples).

Three broad categories of alloy were tested in the literature for use in metal-ceramic restorations (nickel-chrome, high gold and high palladium alloys).

Nickel-chrome alloys

Samples backed by nickel-chrome had lower L* values (Crispin et al 1991 and Kourtis et al 2004), however, O'Neal et al (1987) disagreed. Different Hue values were found (Jacobs et al 1987) compared with high gold backed samples, with the nickel-chrome alloys being less yellow-red than the gold backed alloys.

Jacobs et al (1987) assessed three alloys with three shades of ceramic (A3, B1 and C4). The colour difference between the samples with nickel-chrome backings was statistically different from the other two metal alloys for both shades B1 and C4. The colour change between the gold and nickel-chrome alloys was due to changes in the a* co-ordinate. However, the results were dependent on the opaque ceramic thickness as well as the alloy used.

Crispin et al (1991) assessed the effects of metal alloy and opaque ceramic on the overall colour of the samples. The samples then had shade A1 ceramic added to them. The nickel-chrome backed samples were significantly darker (smaller L*) when compared with the gold-containing alloys. Kourtis et al (2004) tested Vita shade A3 with 0.2 mm thickness of opaque ceramic and 1 mm thickness of dentine ceramic with a variety of metal copings. The nickel-chrome backed samples were significantly darker than high gold samples with a total colour difference (ΔE_{ab}) of 3.29 units. In contrast, O'Neal et al (1987) by means of visual ranking and spectrophotometric analysis of tabs, stated that the non-precious metal-ceramic samples (Ceramco shade 69) were lighter than the precious ones. However, they agreed with Jacobs et al (1987) that changes in Chroma accounted for the main change in the samples.

Unfortunately, the viewing conditions employed were neither stated nor were the colour co-ordinates provided.

High palladium alloys

The effect of this alloy varied. Brewer et al (1985) tested three different alloys overlaid by one shade a ceramic. They found that samples backed by a high palladium alloy were less yellow than samples backed by either a base metal or a precious metal alloy with a high gold content. However, Crispin et al (1991) found that the high palladium-silver alloy samples were more yellow than the samples backed by high palladium-gold alloys.

Barghi and Richardson (1978) found that human observers could not identify a colour difference between metal ceramic samples using 4 different precious metal alloys.

High gold alloys

Nakamura et al (2002) and Koutayas et al (2003) found colour differences (ΔE_{ab}) ranging from 1.53 to 2.1 compared to control samples.

Brewer et al (1985) demonstrated that shade A3 ceramic tabs were more yellow when the high gold alloy was used compared with the base metal and high palladium alloys.

Koutayas et al (2003) tested high gold and titanium alloys. The mean colour difference between the all-ceramic control and the gold alloy with C2 ceramic was 1.42 units (range 0.86 to 2.64), a statistically significant colour difference. Unfortunately, the direction of the colour change was not stated nor was it calculable. The core and dentine ceramic tabs were cemented together, however, the influence of the cement was not discussed.

The gold backed samples were significantly more yellow than nickel-chrome and cobalt-chrome alloys with a total colour difference (ΔE_{ab}) of 0.92 units (Kourtis et al 2004). The ΔE_{ab} values were calculated for these metal combinations (with Vita ceramic). All combinations had differences of at least 1.45 (range 1.45 to 3.79) which indicated a discernable colour difference, with the exception of the nickel-chrome and palladium alloys containing copper (0.92).

Stavridakis et al (2004) tested samples backed by high gold alloys against four other metal alloys with a B1 ceramic thickness of 1 mm (0.1 opaque and 0.9 mm thickness of body). In this study only three samples of each type were tested which may have influenced the range of ΔE_{ab}, the standard deviations for the measurements ranged from 0.1 to 1.5 ΔE_{ab} units. This could have affected the results as the ΔE_{ab} range between different samples was 1.4 to 6.6 units. Following the dentine ceramic cycle there were differences in colour between high copper palladium alloys and the control gold alloys of up to 2.3 ΔE_{ab} units. Following both the dentine and glaze firing cycles' colour differences were found between the high copper palladium alloys and the control alloy of up to 2.8 ΔE_{ab} units. The high copper palladium alloys were significantly darker, greener and less yellow than the samples backed by a high gold alloy. In addition, the conventional palladium alloy tested was significantly lighter

than the control alloy. These authors found that samples which completed glaze firing cycles had significantly larger differences compared with unglazed.

In summary, high gold samples were more yellow than samples backed by nickel-chrome and high palladium alloys whilst one study found the gold alloy samples to be lighter. There were also perceptible colour differences between the all ceramic samples and high gold backed samples of the same shade.

Metal surface treatments

O'Neal et al (1987) studied the effect of the grit of silicone carbide polishing paper and surface conditioning agent on high fusing gold alloy. They investigated whether the grit of polishing paper or the addition of a Jelenko surface conditioner applied to the metal changed the colour of the ceramic (Ceramco shade 69). No discernable difference was noted by the five human observers between tabs polished by different grits of paper. However, when the metal was treated by a surface conditioner prior to ceramic application the tabs were generally darker. Unfortunately, the viewing conditions employed were not stated. Metal surface finish did affect the final colour of the metal-ceramic tabs when measured by spectrophotometer, as the grit of paper used decreased the L* values of the samples decreased the differences were less than 0.5 reflectance units. Changes in Hue and Chroma were greater which allowed the observers to detect colour differences between the samples. However, the authors concluded that the colour differences were clinically insignificant, but no colour difference calculations were completed nor can they be from the data available.

2.5.2 Manufacturer's Variation in the Colour of Ceramic

Different manufacturers with the same shade designation

There was little consistency of ceramic shade production, however, the magnitude of the colour differences varied with ceramic type, shade and manufacturer (Rosenstiel and Johnston 1988):

Jorgenson and Goodkind (1979) found a statistically significant difference between one ceramic shade of different designations from three manufacturers. These shades were purported to be inter-changeable. The colour differences were associated with changes in lightness. Unfortunately, no colour co-ordinates were stated and so the magnitude of these differences could not be identified.

Seghi et al (1986) investigated the colour differences between different brands of ceramics with identical shade designations. They found that brands significantly differed from each other within each colour parameter (L*, a* and b*). The ΔE_{ab} values ranged from 1.84 to 12.15 units (opaque ceramic) and 1.2 to 6.62 units when the samples were fabricated from both opaque and dentine ceramics from three different ceramic brands. The repeatability of measuring device was not discussed in the article.

Rosenstiel and Johnston (1988) found that the colour difference was shade dependent. Colour differences of up to 4.2 ΔE_{ab} units where found for shade A2 (three manufacturers) and a difference of 2.4 ΔE_{ab} units was noted for ceramic of shade B2 (two manufacturers).

O'Brien et al (1991b) confirmed the findings of Seghi et al (1986). The differences between manufacturers were statistically significant with colour difference values ranging from 0.49 to 1.56 ΔE_{ab} units. These colour differences were for opaque and body ceramic samples from four commercial manufacturers.

Colour differences between batches of ceramic

Barghi et al (1985), O'Brien et al (1991b) and Rinke et al (1996) illustrated colour differences between ceramic batches, again with shade dependent differences.

Barghi et al (1985) found that all nine of their observers noted a colour difference between ceramic batches of the same shade. This was the case for three manufacturers tested, it is noted that the production method seems to be consistent as no variation was found between samples from the same batch. Unfortunately, within this study no colour co-ordinate measurements were recorded meaning the results were subject to observer bias.

O'Brien et al (1991) showed a highly significant statistical difference between ceramics from different manufacturers. Their result was shade dependent (A3.5 had higher variations than D4, A2, B2 or A3) and manufacturer dependent (Vita had lower mean variations than the other manufacturers). The mean variation across the batches of ceramic fired three times was 0.85 ΔE_{ab} units; however, the direction was not determined.

Rinke et al (1996) illustrated a range of 2.4 to 9.5 ΔE_{ab} units between different batches of the ceramics (shades A1 and A2).

2.5.3 Effect of Opaque Ceramic Thickness on the Colour of Ceramic

Several studies have shown that the thickness of the opaque layer was important in its ability to mask the colour of underlying metal. The relevant literature revealed that:

- As the thickness of opaque ceramic increased, the direction of the colour change was shade dependent
- Opaque ceramic thickness of 0.3 mm was thought to represent the 'true' colour of opaque ceramic (Barghi and Lorenzana 1982, Terada et al 1989a and 1989b)

Terada et al (1989b) and Dozic et al (2003) showed that the a* and b* values increased as the opaque ceramic thickness increased. The change in L* value was shade dependent but generally increased or remained approximately constant.

Herzberg et al (1972) tested the effect of different ceramic opaque thicknesses on the masking power of a Ceramco ceramic opaque (shade 65). They concluded that opaque thickness and colour were not a linear relationship. It was logarithmic with the amount of reflection increasing as opaque ceramic thickness increased.

Barghi and Lorenzana (1982) attempted to identify the optimum opaque thickness with regard to colour reproduction. As discussed previously this study used seven human observers to assess the colour match. In order to completely mask the metal coping and achieve a match to the control samples an opaque thickness of 0.3 mm

was required but adding more opaque ceramic above 0.3 mm did not noticeably affect the shade of the final samples. The thickness of opaque ceramic did vary between manufacturers and with the shade being tested.

Terada et al (1989a) also found that for all of the metals tested, if the opaque layer (shade A2) were greater than 0.3 mm, then the true colour of the opaque ceramic had been reproduced as the colour co-ordinates stabilised at opaque thicknesses over 0.3 mm. It was stated in the article that the opaque used was more efficient at masking noble alloys than base metal alloys, but no L*a*b* co-ordinates were given.

Terada et al (1989b) found for numerous metal and dentine ceramic combinations there was a perceptible colour difference between samples that had 0.2 and 0.3 mm thicknesses of opaque ceramic. As the thickness of opaque ceramic increased the L* value increased, a* increased (less green to red in colour) and b* increased (more yellow).

Yaman et al (1997) added different quantities of opaque agents to porcelain laminate veneers and found that the L* increased (by ≈7 to 14 units), a* decreased (≈ 2 units) and b* generally decreased (≤5 units) as the amount of opaque was increased.

Dozic et al (2003) found that as opaque ceramic thickness increased both the a* and b* values increased, and the L* variation was shade dependent. The addition of 0.25 mm of opaque ceramic with therefore a reduction in 0.25 mm of translucent ceramic had an effect large enough to be visible for the majority (28/30) of the samples (ΔE_{ab} <1).

Stavrikadis et al (2004) concluded that 0.1 mm thickness of Vita-Omega opaque B1 ceramic was not sufficient to give a reproducible colour following simulated dentine and glaze firings. The colour differences between samples were 2.8 to 3.7 ΔE_{ab} units, however, after application of 0.9 mm of Vita-Omega B1 body ceramic the differences were <1 ΔE_{ab} unit. These findings confirmed Barghi and Lorenzana's (1982) and Terada et al's (1989a and 1989b) findings that 0.1 mm thickness of opaque ceramic was not sufficient to give a true representation of the opaque's colour. However, they confirmed that the addition of body ceramic decreased the overall colour difference.

Opaque Surface Finish

Obregon et al (1981) found for shades A3 and B1 that Hue, Value and Chroma changed when the opaque surface was altered from dull to glossy. A glossy opaque layer increased the Value but had the opposite effect on the Chroma recorded. The Hue changes were shade dependent.

In summary the metal used, manufacturer, batch, opaque thickness and opaque surface finish had a visual effect on the colour of the sample/restoration. These colour differences were likely to a clinical impact.

2.5.4 Methods of Ceramic Condensation and their Effect on the Colour of Ceramic

Ceramic condensation was defined by McLean (1979) as:

> *The process of packing (ceramic) particles together and of removing the liquid binder*

Ceramic application to metal required treatment of the metal prior to application of the first layer of opaque ceramic. The metals must first be cast to the desired shape via the lost-wax technique. Depending on the metal and the ceramic manufacturer's instructions, the metals are usually then ground, sandblasted, cleaned and then oxidised.

The ceramic powders are mixed with distilled water or modelling liquid producing a slurry which is then applied and shaped to form the restoration. The ceramic slurry is generally applied with a brush. First, wash opaque is applied with a brush or sprayed-on and then vacuum-fired. Shade-designated opaque ceramic is subsequently applied and fired in a similar manner. These individual processes vary slightly between manufacturers. The ideal, uniform thickness of the opaque layer is between 0.2 and 0.3 mm. Dentine and enamel ceramics can then be applied. There is a variety of methods employed to condense ceramics. Varying methods were described by Naylor (1992):

- Capillary Action:

  The technique of blotting a wet build-up with absorbent paper uses surface tension (capillary action) to withdraw the liquid and pack the porcelain particle together.

- Vibration:

  The easiest and simplest form of vibration is created by passing a serrated instrument over the neck of a haemostat in which the restoration is held. Alternatively, if the restoration is left on the cast, the entire cast can be tapped or vibrated.

- Alternative Methods of Vibration:

There are several devices on the market to provide mechanical vibration, such as vibrating brushes, spatulas and ultrasonics.

- Dry Powder Addition:

The technique requires that dry powder be sprinkled on an area of wet porcelain, using the existing liquid to moisten the powder additions.

Both methods of vibration draw additional moisture to the surface, where it can then be removed by blotting with a tissue.

Ceramics can shrink by up to 35% (Schrader et al 1986) during the firing process and as a consequence the slurry has to be overbuilt. The process of ceramic build-up and the addition of different ceramics to the restoration are repeated until the desired shape and colour of restoration are fabricated. It is also noted that furnaces vary in their stated temperatures and as a consequence they should be calibrated and tested frequently. The manufacturer's instructions are occasionally adjusted to obtain the desired ceramic finish. If the ceramic is over-fired there may be pyroplastic flow. If insufficient firing occurs the physical and optical properties may be affected. Most contemporary ceramics are fired in a vacuum furnace.

Fired dental ceramic consists of ceramic particles which have fused. The process is not identical every time, due to a variety of factors which can result in the ceramic having pores, voids or cracks.

2.5.5 Effect of Body Ceramic Thickness on Colour

The studies discussed in this section have looked at the effect of dentine ceramic thickness on the final colour of the metal-ceramic sample or restoration. However,

they were not all comparable due to the different metals and ceramics used. In addition, the criteria and method of assessment of the colour of the samples varied. Although, the influence of ceramic thickness on colour has been investigated, the effect of the thickness of ceramic slurry fired at one time has not been studied.

Brodbelt et al (1980) illustrated that transmission of light through dental ceramic was a function of the ceramic thickness. As ceramic thickness increased the amount of direct transmission and light scattering decreased. It also illustrated the importance of the background colour as light that is transmitted will be affected by the background and this will influence the final colour recorded.

Studies by Dagg et al (2004) and Vichi et al (2000) found statistically significant colour differences between ceramic tabs of varying thicknesses with the 2 mm tabs being matched better by observers than thinner tabs. Both these studies found that if the ceramic was 2 mm thick the underlying coping had no effect on the final shade. Nakamura et al (2002) found significant colour differences when type IV gold backed specimens were compared with ceramic veneered specimens until the overlying ceramic thickness reached 1.6 mm.

Dozic et al (2003) found that, for an overall ceramic thickness of 1 mm, as the thickness of translucent ceramic decreased the 1976 C.I.E. a* and b* values increased. This indicated that the opaque layer had a significant effect on the final colour of ceramic at thicknesses <1 mm.

Douglas and Przybylska (1999) found that at ceramic thickness of <2 mm, all-ceramic samples matched the shade tab better than those of metal-ceramic. The colour differences between varying thicknesses of the ceramic and the shade tab tested were large, the ΔE_{ab} range was ≈1 to 10 units for the three shades tested (A1,

C2 and A3). Unfortunately, the actual colour co-ordinates for each thickness were not published and therefore no colour differences could be calculated between the ceramics of different thicknesses. Although, as the colour difference between the shade tabs and the samples of different thicknesses varied, it was concluded that a difference in shade between the thicknesses existed.

Jacobs et al (1987) used both human observers and spectrophotometric measurements to assess the colour differences between metal-backed ceramic samples with gold-palladium, nickel-chrome and high palladium alloys:

1. For the gold-palladium backed alloys, the three shades of ceramic tested showed a decrease in Value and an increase in Chroma as the thickness of ceramic increased with the exception of the Value of the shade B1 samples which remained approximately constant. However, only the differences between 0.5 and 1 mm dentine ceramic were statistically significant. The Hue of shades A3 and C4 ceramic changed towards yellow-red from yellow. Visual changes in the colour were obvious to the observers at ceramic thicknesses of between 0.5 and 1 mm for shades A3 and C4. However, if the thickness were 1 mm the differences were less visible for all shades.

2. For the nickel-chrome backed samples, the results were similar. However, the shade B1 and C4 ceramics did not increase in Chroma as the thickness of ceramic increased. The observers found visible colour differences between A3 ceramic of 1 and 1.5 mm.

3. High palladium samples show similar results to the gold-palladium alloy samples with regard to their Hue changes. Value decreased with increased ceramic thickness

for ceramic of shade A3 and C4 only. The only apparent change in Chroma was an increase as ceramic thickness increased for shade A3 only. The visual assessments were similar to the gold-palladium backed samples, except that the changes seen with ceramic of shade B1 were more obvious.

Terada et al (1989a) tested several different base metal and precious metal alloys with shade A2 ceramic. They found that, regardless of alloy type and ceramic thickness (0.1 to 0.5 mm), that as ceramic thickness increased, the L* decreased, a* increased and b* increased.

Brewer et al (1991) found that size of the L* and b* change was dependent on the metal coping used. An additional dentine layer caused a decrease in L* and b*. This was true with the exception of the b* values of the high gold backed samples, where the opposite trend was found.

Jorgensen and Goodkind (1979) found a statistically significant decease in the Value of all of the shades of ceramic tested (seven in total) as the ceramic thickness increased. However, no significant differences in Chroma or Hue between the samples of any shade were found.

Barghi and Lorenzana (1982) used human observers to match metal-ceramic samples to a control shade guide. The agreement of the observers was dependent on the shade of ceramic and the ceramic manufacturer. Conclusions drawn in this research showed that as additional body ceramic was added the visual appearance of the samples changed. Unfortunately, these assessments were subject to bias and unreliability and there was no indication of the direction of colour change.

In summary, these studies showed calculated visual colour changes in the ceramic as the thickness of dentine ceramic increased. Dentine ceramic must be between 1.5 and 2 mm thick to fully mask the underlying metal and opaque ceramics. The results appeared conflicting:

- The Value or L* values decreased with increased ceramic thickness according to Jacobs et al (1987), Terada et al (1989a and 1989b) and Brewer et al (1991), however, Jorgensen and Goodkind found the opposite.
- The Hue/Chroma or a*/b* values were shown to increase by Jacobs et al and Terada et al but Jorgensen and Goodkind (1979) found no difference as the thickness of dentine ceramic increased. In contrast, Brewer et al (1991) found the a* to increase but the b* to decrease.

2.5.6 Effect of Ceramic Firing Conditions on Colour

Claus (1989) stated that the following influenced the physical properties and possibly the colour of ceramic:

- Firing cycle
- Maximum firing temperature
- Rate of temperature rise
- Length of 'hold' time
- Rate of cooling
- Presence of vacuum during firing

In addition, it has been postulated that the number of firing cycles has an influence on the colour and physical properties of ceramic produced. No research was identified that related the rate of cooling to colour changes.

2.5.6.1 Ceramic Firing

Number of firings

Barghi and Goldberg (1977) found no significant changes in colour after five firings and minimal but acceptable changes if the ceramic was fired up to ten times. The samples were viewed in both natural and artificial lighting. It was noted that air-fired ceramic was affected more whilst the change seen in vacuum-fired ceramic was a smaller Value.

Barghi and Richardson (1978) reaffirmed these observer findings. They found no significant changes in the colour of the samples after six firings. However, a minimal but acceptable change after nine firings was noted. These differences were noted in both natural and artificial lighting by human observers.

Barghi (1982) assessed changes in the colour of metal ceramic tabs following repeated firings. Seven observers were used to visually assess the tabs. No visual changes were detected following five firings, however small changes were noted by six of the seven observers when the tabs were fired between six and nine times.

These results suggested that repeated firing (up to six times) of vacuum-fired ceramic did not result in colour changes obvious to human observers. However, further firing (up to ten times) gave a slight colour change which was visible. Unfortunately, these studies did not state which criteria were used to assess a colour match and no testing of the examiner's repeatability was completed. The problems of using human observers have been discussed, however, these studies provided a good visual basis for ceramic colour changes due to firing.

Jorgensen and Goodkind (1979) found no significant differences in the colour co-ordinates of three shades of body ceramic, of 2 mm thickness, from one manufacturer across the number of firings tested (2, 5, and 10 times under vacuum). Unfortunately, the colour co-ordinates were not provided in this paper and no colour differences (ΔE_{ab}) were given. It was noted that the Hue and Chroma changed as the number of firings increased. It was impossible to ascertain if these differences gave a perceptible colour difference.

Hammad and Stein (1991) fabricated samples with a total ceramic thickness of 1 mm using one shade (B2). The samples were fired a total of five times with no statistical difference between the mean Hue, Value and Chroma values gained between the body ceramic firings. Unfortunately, no colour co-ordinates are given to allow further analysis.

O'Brien et al (1991b) found that the colour differences (ΔE_{ab}) between three and six firings were equal to one unit when opaque and body ceramics were considered together (total ceramic thickness was 2.05 mm). An average of 1 ΔE_{ab} unit was calculated across the three manufacturers and six shades (range of ΔE_{ab} was 0.16 to 2.07 units). These differences surprisingly were not statistically different across the tabs. It was also not possible to identify the direction of colour changes seen.

Ceramic samples were fired 2, 5, 6 and 10 times in these studies. The results indicate that there was a colour change in the samples with repeated firing, however, the direction of this was not clear. In addition, the number and type of cycle had an

effect on the colour (Stavrikidis et al 2004), although quantitative data could not be obtained from their results.

Repeated firing has been shown to the affect the amount of fluorescence of dental ceramic (Ecker et al 1985). The amount of fluorescence decreased as the number of firings increased across four manufacturers tested. A relationship between this effect and the final colour observed has not been identified in the dental literature.

2.5.6.2 Ceramic Thermal History

There were numerous factors stated by Claus (1989) in the thermal history of a ceramic that will affect its colour. The influence of the furnace pressure, firing time, rate of temperature increase and hold time on shade does not seem to have been investigated. However, Claus (1989) found translucency was affected by these factors. Changes in translucency may affect the colour of the samples as the underlying colour will influence the colour observed.

Maximum Firing Temperature

The maximum temperature of the furnace is stated by the ceramic manufacturer. Several studies (Rosenstiel and Johnston 1988, Claus 1989, Hammad and Stein 1991 and Lund and Piotrowski 1992) have shown the effect of grossly under- or over-firing ceramic on its colour:

As the total firing temperature increased the amount of translucency of the samples increased for two ceramics, shades 530 and 569 of Vita VMK 68 (Claus 1989). No

definitive conclusions can be drawn as the effect on the colour of the samples cannot be demonstrated.

Hammad and Stein (1991) assessed the effect of increasing the ceramic furnace temperature with regard to the final colour of the ceramic. Metal-ceramic samples were fabricated in a standard manner, except that some were fired at temperatures 35 (and 70) °F higher than the manufacturer's recommended maximum. As the maximum firing temperature increased both the Hue and Value increased, however, the Chroma of the samples remained approximately constant. A difference between ceramic manufacturers was seen, Vita VMK 68 showing larger changes than Ceramco II for both the Value and Chroma measurements.

However, Rosenstiel and Johnston (1988) tested the effect of increasing or decreasing the recommended maximum firing temperature by 30°C and found no statistical difference. Colour differences of 0.4 ΔE_{ab} units (temperature increase) and 0.3 ΔE_{ab} units (temperature decrease) were demonstrated which were deemed by the authors to be clinically undetectable.

2.5.7 Ceramic Porosity

2.5.7.1 Methods to Assess Ceramic Porosity

Several methods have been used to assess the porosity of ceramic, including:

- Direct counting of the number of pores and average pore size in a set sample area and then calculating the percentage porosity (Semmelman 1957)
- Specific gravity analysis (Evans et al 1990)

- Apparent porosity analysis by using the density of water as a constant (Fleming et al 2000 and Palin et al 2001)
- Measurement of pore size on photomicrographs (Cheung and Darvell 2002, Albakry et al 2004 and Geirsson et al 2004)
- Porosity fraction calculation from photomicrographs (Guazzato et al 2004)
- Point counting method (Geirsson et al 2004)
- Porosity testing by analyses of true density measurements (Zhang et al 2004)

2.5.7.2 Causes of Ceramic Porosity

The evidence from the dental literature suggested that there were several causes of porosity in sintered ceramic; however, not all ceramic types had the same constituents, particle size or used the same binder which altered their densities (Meyer et al 1976). These may have affected the porosity measurements. Other factors may also have affected the porosity:

1. Presence of a vacuum. Air firing used to be common practice, however, vacuum firing reduced the total porosity (Jones and Wilson 1975) and therefore increased the density of the materials (Meyer et al 1976). The pore size (Semmelman 1957) also decreased when the slurry was fired under vacuum.

2. Ceramic sintering time has been shown to affect the density of the resultant ceramic. Two studies (Cheung and Darvell 2002, Jones and Wilson 1975) found that the porosity of VMK-68 ceramics increased with sintering time. The porosity was co-dependent on sintering time and maximum temperature, although the maximum firing temperature had the larger effect. It should be noted that a certain amount of sintering was required to produce this result; below this time the samples were more

porous whilst the amount of sintering was manufacturer specific. Jones and Wilson (1975) also demonstrated that smaller particle sizes (<5μm) gave increased porosity in the final ceramic. In contrast, Anusavice and Lee (1989) found that under-fired porcelain had increased fracture toughness. They linked this to an increased number of pores which acted as crack stoppers, thereby increasing the fracture toughness of the under-fired samples.

3. When the firing temperature was decreased below the recommended levels the porosity increased (Anusavice and Lee 1989). Cheung and Darvell (2002) found a combination of high temperature and short sintering time to produce samples with the least porosity. Increasing the firing temperature too much produced samples that were more porous (Borgia et al 1996). However, these effects were dependent on the type of ceramic used as Meyer et al (1976) found that opaque ceramics did not change in density when the firing temperature increased.

2.5.7.3 Consequences of Ceramic Porosity

Porosity has been linked with several problems. It has been shown to reduce the aesthetics (McLean and Hughes 1965), strength (McLean and Hughes 1965), increase plaque and stain accumulation (Koseyan and Biswas 1976) and increase the abrasiveness (DeLong et al 1986, Kelly et al 1989, Jacobi et al 1991), if the ceramic sub-surface was exposed. The current literature had little evidence linking structural porosity to colour.

Porosity and Colour

Rosenstiel and Johnston (1988) illustrated the effect of under- and over-condensing ceramic prior to sintering. They showed that the L*, a* and b* co-ordinates changed

depending on the amount of condensation. Five samples of each group were fabricated and the average colour measurements were used for comparisons and it was stated that errors due to fabrication were greater than measurement variables. The samples were under-condensed by air drying only and over-condensed by placing small increments followed by vibration and blotting. Colour differences of 1.1 and 0.7 ΔE_{ab} units were found between the control samples and the under-condensed and over-condensed samples respectively. The extrapolated difference between the over- and under- fired samples was 1.5 ΔE_{ab} units. All three colour co-ordinates were lower when the samples were under-condensed.

Evans et al (1990) examined four different ceramics of shade B2 following ceramic condensation by four different methods. They found no statistical difference between the L* value of the ceramics condensed by different methods. However, the a* and b* values were affected, although the differences between the values were small. For VMK 68 shade B2, when the ultrasonically condensed samples were compared with the non-condensed samples a* and b* increased. Although only the b* increased to a statistically significant level. Extrapolated data showed a ΔE_{00} of 0.55 units between these two samples. Their results, however, showed no difference in apparent specific gravity of the samples regardless of condensation method.

The method of condensation of the ceramic slurry had an uncertain influence on the porosity or density of the final ceramic. However, it was concluded that under-condensing the slurry affected the L*, a* and b* values. These values were generally lower for under-condensed samples (Rosenstiel and Johnston 1988 and Evans et al 1990). However, the method of assessment and amount of glaze affected these readings (Lee et al 2002).

Powder to Liquid Ratio and Porosity

Zhang et al (2004) found that the ratio of powder to liquid in the ceramic slurry had no influence on the translucency of the fired ceramic. Although, they concluded that this ratio had an effect on the porosity and density measurements. Unfortunately, they did not measure the colour of samples, only translucency.

2.6 Summary

There is a reliance on the human eye for colour assessment. However, there are well-documented difficulties when assessing colour by eye as a result colour-measuring devices have been developed to aid assessment. These devices are relatively new and require further investigation to assess their reproducibility, accuracy and correlation with human observations.

The colour of dental ceramic is dependent on both the manufacturer and mode of fabrication. The effect of small colour changes as a result of fabrication technique changes may not have a clinical impact when considered individually. However, several subtle changes in fabrication may result in an overall visible colour change.

Colour changes were measured numerically and by human observers with subsequent statistical analyses. Many colour changes were considered to be statistically significant but the actual changes were negligible. Alternatively, substantial colour changes were occasionally dismissed as the statistical analyses, which were not adequately powered, did not reach significance.

CHAPTER 3: AIMS OF THE STUDY

3.1 Statement of the Problem

Determination of the colour of a tooth is a subjective procedure. Instruments claiming to be able to record tooth colour in a way that a dentist and dental technician would find helpful were first developed 30 years ago. Improvements in electronics have led to revised equipment which can be more easily used in dentistry. However, there was little work that validated such instruments and permitted an understanding of the colour dimensions recorded. The fabrication of ceramic and metal-ceramic samples of consistent colour is not an easily reproducible process. The literature showed that there was little information on the effect of mode of fabrication for building porcelain samples on colour dimensions.

3.2 Aim

To identify the influence of the technique for building and condensing porcelain on the colour dimensions recorded.

3.3 Objectives

This investigation examined the following hypotheses:

1. There was no difference between the measurements of colour co-ordinates of dental ceramic made with two different colour measuring devices (IdentaColor II and Spectraflash SF600)
2. Variation in the mode of fabrication of porcelain samples will have no effect on the colour co-ordinates of ceramic or its porosity

CHAPTER 4: MATERIALS AND METHODS

MATERIALS

IdentaColor II (Identa A/S ®, Holbaek, Denmark), serial number: 2012

Vita Vitapan ® classical shade guide (Vita-Zahnfabrik ®, Bad Säckingen, Germany), lot numbers:

- J017B027C0 (shade guide 1) and J017B027C0 (shade guide 2)

Addition-cured polyvinylsiloxane impression material:

- Coltène/Whaledent Limited ®, West Sussex, United Kingdom
- Aquasil Putty, Dentsply Limited, Surrey, United Kingdom

Acrylic resin (DuraLay resin®, Prestige Dental Products Limited, Bradford, United Kingdom)

Separating agent (Iso Stift, Balco Processing Products, Birmingham, United Kingdom)

Die stone material (Prima Rock, Whipmix Corporation, Louisville, Kentucky 40217, United States of America)

Thinner (Balco Processing Products)

Copper-plating machine (Wila Acruplat, Wieland Edelmetalle GmbH and Company, Pforzheim, Germany)

Silver Flake (Balco Processing Products)

Vita VMK 95 (Vita-Zahnfabrik ®, Bad Säckingen, Germany) dentine ceramic powder, lot numbers:

- 5124 and 7569 (B1)
- 7600, 7603 and 7489 (A3)
- 4676, 6065, 7189 and 7344 (D4)

Platinum foil (0.025 inches thick, Skillbond Direct Limited, Buckinghamshire, United Kingdom)

Vacuum porcelain furnace (Detrey Multimat Mach 3 furnace, Dentsply Limited, Surrey, United Kingdom)

Dual-beam spectrophotometer (Spectraflash ® SF600, Datacolor International, Lawrenceville New Jersey, United States of America)

Colour management software (DataTools QC, Datacolour International)

Investment material (Moldavest Futura, Heraeus-Kulzer Limited, Newbury, United Kingdom)

Nickel-Chrome ingots (Heraenium ® NA, Heraeus-Kulzer Limited, United Kingdom)

Vita VMK 95 (Vita-Zahnfabrik ®, Bad Säckingen, Germany) wash opaque ceramic,

lot numbers:

- 7379 and 7483

Vita VMK 95 (Vita-Zahnfabrik ®, Bad Säckingen, Germany) paste opaque ceramics, lot numbers:

- 6444 and 6376 (B1)
- 3710, 7730 and 7552 (A3)
- 6827 and 7432 (D4)

Buehler Isomet 1000 Saw with Diamond wafering blade (Coventry, United Kingdom)

Buehler Isocut Plus Cutting Liquid (Coventry, United Kingdom)

Scanning Electron Microscope (Phillips SEM 505, FEI UK Ltd, Cambridge, England)

Image Analysis Software (Image J, version 1.36, Wayne Rasband, National Institutes of Health, United States of America)

METHOD

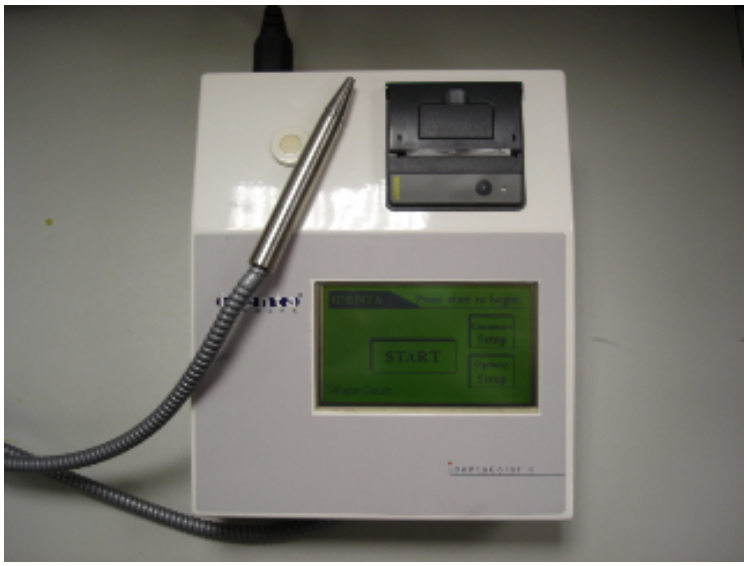
4.1 Microspectrometer (IdentaColor II) Measurement of Porcelain Tabs (Expts. 1 to 3)

The shade and colour co-ordinates recorded by a microspectrometer (IdentaColor II) were assessed while varying the calibration method, ambient lighting, day of measurement using two types of tab surface.

4.1.1 Microspectrometer (IdentaColor II)

An intra-oral shade matching device, IdentaColor II, was used. This consisted of a microspectrometer with a control unit and metal probe connected by fibre optic cabling. The probe contained an aperture of one millimetre diameter to measure the shade of a sample (Figure 4.1). The investigator operated the device throughout the thesis.

Figure 4.1. IdentaColor II



4.1.1.1 Data Transfer and Calculations for Experiments 1 to 3

All measurements from IdentaColor II were transferred to a personal laptop computer via a communication cable. Software from Identa A/S ® was used to record the colour components that IdentaColor II measured, these were directly imported into a text editor (Microsoft ® Notepad Version 5.1). The data were prepared, exported to spreadsheets (Microsoft ® Excel 97) and the following calculations were completed:

1. The first measurement of each sample was discarded from the set of 31.
2. The mean value and coefficient of variation of each colour component were calculated for the remaining thirty measurements (numbers 2 to 31). Alternatively, the most common shade selected from each data set was stated as well as the frequency with which that shade selection occurred.
3. When the coefficient of variation of at least one colour component in any given data set was greater than 1%, an additional set of calculations was made: The colour difference (ΔE_{00}) between the mean of the thirty measurements and each individual measurement was calculated.

4.1.2 Porcelain Shade Guide Tabs (Vitapan Classical)

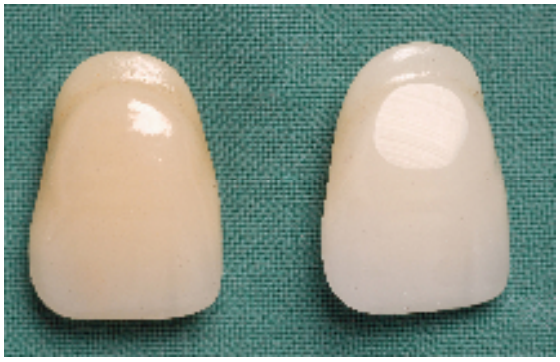
Shade tabs were taken from two porcelain Vita Vitapan ® classical shade guides. The shade tabs selected were shades B1, A3 and D4 and each of these three shades of tabs were taken from each shade guide.

4.1.2.1 Preparation of Porcelain Shade Guide Tabs

The three digit number from the reverse of the incisal area of each tab and the corresponding conventional shade identification were recorded. The incisal codes were not visible during measurement therefore blinding the examiner to the conventional shade designation of the tabs. Only when the measurements were completed were the incisal codes revealed.

The tabs from shade guide 1 were left unaltered while those from shade guide 2 had a flat, three square millimetre area ground onto their facial aspects (Figure 4.2) using a lathe.

Figure 4.2. Porcelain Shade Guide Tabs



The codes from the shade tabs used were:

- shade guide 1: 047, 209 and 210
- shade guide 2: 089, 044 and 124

The tabs were placed in the room where testing was completed for 24 hours prior to testing. This followed the recommendation of The Society of Dyers and Colourists (2002).

4.1.2.2 Mounting Procedure for Porcelain Shade Guide Tabs

A custom holder was made for the shade tabs: approximately two centimetres thickness of dental stone was added to the horizontal table of a Bachmann parallelometer, allowed to set and retention grooves were marked in the stone (Figure 4.3). Polyvinylsiloxane impression putty was mixed and formed into a rectangle approximately 1.5 centimetres thick which was added to the dental stone. A shade tab was placed into the putty and the probe of the IdentaColor II was used, as a tool to align the surface to be measured, to make the tab surface parallel to the horizontal table of the parallelometer. The putty mold acted as a holder for the shade tabs whilst measurements were made and was marked to allow measurement of the same area on each tab. All porcelain shade guide tabs were mounted in this manner prior to colour measurement.

Figure 4.3. Mounting Apparatus

4.1.3 Custom-Made All-Ceramic Samples

The fabrication of samples of specific dimensions was facilitated by use of a master model. The construction of a stable master model of known dimensions allowed numerous samples of known dimensions to be made.

4.1.3.1 Fabrication of the Master Samples and Model

DuraLay resin ® samples were constructed of 1, 1.5, 2, 3, 4 and 5 millimetre thicknesses. The resin tabs were ground using the lathe's squaring block to make tabs which had two flat surfaces that were parallel to each other. The diameter of the smallest flat surface was 5 mm.

The resin samples were laid on a glass slab coated with a separating agent, Iso Stift, and a model in die stone was poured of the specimens. After the stone had fully hardened, a putty and light-bodied addition-cured polyvinylsiloxane impression was made of all of the die stone model.

The impression was painted with an isobutylmethylkelon thinner, air dried and attached to a jig. A silver suspension, Silver Flake, was applied to the areas to be copper-plated and the impression was then immersed in the plating bath. Several copper-plating cycles were completed:

1. Three cycles of 9 hours and 30 minutes at 50 milliamps
2. Three further cycles of 9 hours and 30 minutes at 300 milliamps.

Following copper-plating the impression was removed from the bath, washed and dried. A wax periphery was created before acrylic resin (approximately 1 centimetre

thickness) was applied to the underside of the impression to assist in the manipulability of the master model.

4.1.3.2 Fabrication of Dentine Ceramic Samples

Ceramic samples were constructed of Vita VMK 95 metal-ceramic dentine porcelain using a standardised method:

1. The master model of the selected thickness had platinum foil burnished into it. The chosen ceramic powder was mixed with distilled water on a mixing palate. This slurry was placed onto the platinum foil in the model.
2. The slurry was condensed by hand vibration and then blotted dry with absorbent tissue paper. This was repeated until no further water was absorbed from the slurry's surface. The foil and slurry were removed and placed in a Detrey Multimat Mach 3 furnace.
3. The ceramic tabs were fired according to the manufacturer's instructions, the furnace reached a maximum temperature of 930°C under vacuum (Appendix A contains full details of the furnace cycle). The samples were allowed to cool.
4. The platinum foil was removed from the tabs and additional porcelain, from the same batch, was added to compensate for firing shrinkage and the thickness of the platinum foil. It was condensed and dried as described above and then re-fired using the cycle in Appendix A. This process was repeated up to five times to create tabs of the desired shape and size.
5. The samples were ground to give flat surfaces and subsequently polished with polishing stones and wheels.

Mitutoyo CD-6"C digital callipers were used to verify the dimensions of the ceramic

tabs at five points on their surface. The thickness of the tabs one millimetre from each corner and at the centre of the tabs was measured. Any necessary adjustments were made with polishing wheels and stones.

Each tab was marked on its vertical wall and then assigned a random code. The code, shade and thickness of the samples were stored and were not available during measurement.

4.1.3.3 Mounting Procedure for Custom-Made All-Ceramic Samples

These tabs were mounted using the method described in section 4.1.2.2. However, a new polyvinylsiloxane holder was made to accommodate the different shape of these tabs. All of the custom-made all-ceramic samples were mounted in this manner prior to colour measurement.

4.1.4 Measurement Procedure (Colour)

The vertical arm of the parallelometer was adjusted until the probe was positioned over the centre of the tab. The arm was then fixed to allow only vertical movement. The same point on each tab was measured by lowering the arm with IdentaColor II's probe attached. The α, β and γ colour values were recorded for all experimental conditions, unless otherwise indicated.

All electrical devices excluding the IdentaColor II device and a personal laptop computer were turned off. The display screen of the laptop was closed and the IdentaColor II's screen was covered during the measuring process.

4.1.4.1 Effect of Re-calibration using IdentaColor II (Expt. 1)

Experiment 1 was carried out in the dark room to prevent external light striking the test samples. All over-head lighting was turned off and any spacing around the door was covered.

Shade guide tabs 210 and 089 (shade A3) were chosen for this experiment.

Experiment 1A: IdentaColor II was calibrated at the beginning of each data set and subsequently when the device requested. The shade tabs were measured thirty-one times without moving the probe.

Experiment 1B: IdentaColor II was re-calibrated after every measurement. The probe was moved to the recalibration tile before returning it to its location over the centre of the shade tab. The tabs were measured a further thirty-one times.

4.1.4.2 Effect of Lighting Conditions using IdentaColor II (Expt. 2)

The IdentaColor II device was re-calibrated before the measurement of each tab and subsequently if it requested.

All of the porcelain shade guide tabs (numbers: 047, 209, 210, 089, 044 and 124) were chosen for this experiment. The mounting protocol described previously was used (sections 4.1.2.2). In addition to the dark room described previously a dental surgery was used, its colour-corrected ceiling lights were turned on and the sample

was placed on the head rest of the dental chair but the dental operating light was not switched on.

The six porcelain shade guide tabs were measured thirty-one times in the dental surgery and a further thirty-one times in the dark room.

4.1.4.3 Effect of Time using IdentaColor II (Expt. 3)

The IdentaColor II device was re-calibrated before measurement of each tab and subsequently if it requested.

The shade guide tabs numbered 047, 209, 210, 044, 089 and 124 were used. These tabs were mounted as described in section 4.1.2.2. In addition, custom-made all-ceramic tabs 1, 2, 3, 4 and 5 mm thick of shades B1, A3 and D4 were fabricated using Vita metal-ceramic dentine, mounted and encrypted as described previously (section 4.1.3). Three tabs of each shade and thickness were produced. Both sample types were measured using the method described previously under dental surgery lighting (section 4.1.4.2).

Experiment 3A: The six shade guide tabs were measured thirty-one times on days 1 and 2.

Experiment 3B: The six shade guide tabs were measured thirty-one times on days 1 and 2 and the shade selection was recorded.

Experiment 3C: The forty-five custom-made all-ceramic tabs were measured thirty-one times on days 1 and 2 and the shade selection was recorded.

The results under dental surgery lighting (experiment 2A) were used as day 1 results for experiment 3A. A further set of measurements were taken and these constituted the day 2 results for experiment 3A.

4.2 The Effects of Type and Thickness of Tabs on Spectrophotometric Measurements using Spectraflash SF600 (Expt. 4)

Custom-made tabs were fabricated to varying thicknesses were measured by the spectrophotometer described below and were transferred as described in section 4.2.1.1. These processes were repeated for the porcelain shade guide tabs described beforehand.

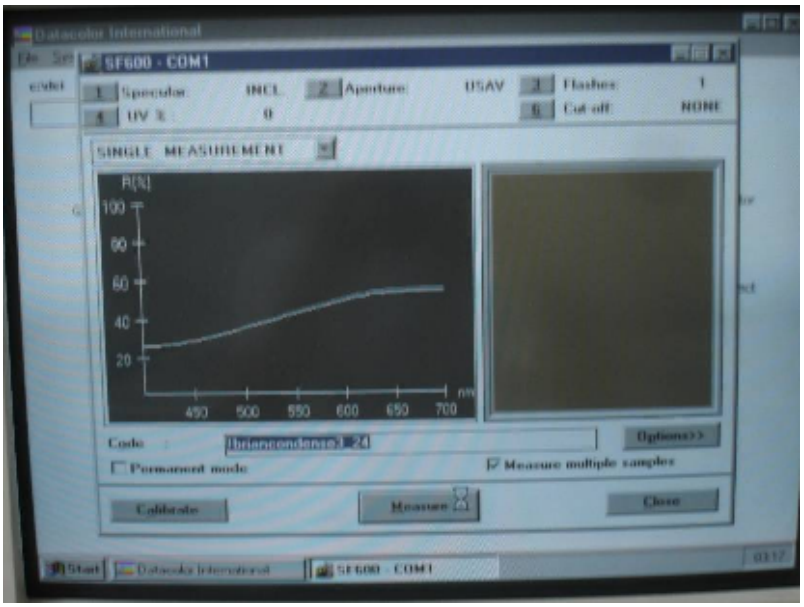
4.2.1 Spectrophotometer (Spectraflash SF600)

A dual-beam spectrophotometer, Spectraflash ® SF600, was used (Figure 4.4). It was stored in a colour-measuring suite and was allowed to warm-up for thirty minutes prior to calibration. Calibration was completed using three coloured tiles (white, black, green) of known colour co-ordinates. Measurements were recorded by the device from 400 to 700 nanometres at 10 nanometre intervals. The D_{65} illuminant providing diffuse illumination, the 8 degree viewing field and the specular inclusion (SCI) setting were used. The ultra small aperture (6.5 mm illuminated and 2.5 mm measured diameter) was used for colour measurement. The device recorded the colour of a sample and described them using the C.I.E. 1976 L*a*b* system.

Figure 4.4. Spectraflash SF600

This device was connected to a personal desktop computer with a colour management software package (Figure 4.5). This enabled the colour measurements to be stored.

Figure 4.5. Reading from Colour Management Package



4.2.1.1 Data Transfer and Calculations for Experiments 4 to 8

All readings were transferred to a personal desktop computer from the Spectraflash SF600 via a communication cable. The DataTools QC colour management software program was used to export the colour measurements. These were directly imported into a text editor (Microsoft ® Notepad Version 5.1), copied to spreadsheets (Microsoft ® Excel 97) and the following calculations were completed:

1. The first measurement of each sample was discarded from the set of 31.
2. The mean 1976 CIE L*, a* and b* values and their coefficients of variation were calculated of the remaining thirty measurements (numbers 2 to 31).
3. When the coefficient of variation of at least one colour component in any given data set was greater than 1%, an additional set of calculations were made: The colour difference (ΔE_{00}) between the mean of the thirty measurements and each individual measurement was calculated.

4.2.2 Porcelain Shade Guide Tabs (Vitapan Classical)

The shade guide tabs, mounting procedures and the encryption method from section 4.1.2 was used.

4.2.3 Custom-Made Tabs

The master model described previously was used to create these samples.

4.2.3.1 All-Ceramic Tabs

Fabrication of Custom-Made All-Ceramic Tabs

The method described previously was used to fabricate one new thickness (1.5 mm) of custom-made all-ceramic samples (section 4.1.3.1). The remaining tabs fabricated for the previous experiments were used in this experiment.

4.2.3.2 Metal-Ceramic Tabs

There were several additional stages needed to produce metal-backed ceramic tabs that could be measured by a spectrophotometer:

Fabrication of Custom-Made Metal-Ceramic Tabs

A new model in die stone material was poured of the one millimetre master acrylic resin tab from section 4.1.3.1 and a separating agent applied as required. The lost-wax technique was employed to create nickel-chrome tabs of one millimetre thickness. Firstly, molten wax was poured into the molds, trimmed to shape and carefully removed. The wax tabs were then mounted with three millimetre diameter sprue wax into a casting ring and an agent to decrease surface tension was sprayed over the wax (Vacufilm). The ratio of eleven millilitres of liquid to sixty grams of powder of the investment material (Moldavest Futura) was vacuum mixed for one minute. The investment material was poured into the casting ring on a vibrating table. Following completion of the setting of the investment, the top of the investment was removed using the lathe. The ring was placed in a burn-out furnace at 900°C for one hour and then into an automated induction casting machine

(Heracast Q). Casting was completed using standard laboratory methods with nickel-chrome ingots (Heraenium ® NA). The ring was removed, allowed to cool on the bench and the castings were de-invested. The sprues were removed using a cut-off disk.

The nickel-chrome backings were then prepared to receive porcelain. The backings were ground with a brown stone which removed any blemishes. The stone was moved in only one direction over the backing on one side. The ground sample was sandblasted with 50 μm aluminium oxide particles and cleaned with a steam cleaner. The samples were allowed to dry and were then placed with the sandblasted surface facing upwards in the vacuum porcelain furnace. The samples were de-gassed at a maximum temperature of 980°C. They were removed from the furnace and left to cool.

One layer of Vita VMK 95 wash opaque porcelain was applied over all of the oxidised tabs and fired in the vacuum porcelain furnace. The porcelain manufacturer's instructions were followed and the cycle reached a maximum temperature of 950°C under vacuum (Appendix B contains full details of the furnace cycle).

One uniform layer of shade designated Vita VMK 95 paste opaque porcelain was applied to the tabs and fired in the vacuum porcelain furnace according to the porcelain manufacturer's instructions. The furnace reached a maximum temperature of 930°C under vacuum (Appendix C contains full details of the furnace cycle).

The thickness of the opaque layer was modified and verified using the method in

section 4.1.3.2. The final opaque ceramic layer produced was 0.2 mm.

Vita VMK 95 dentine ceramic was added to the samples in a standardised fashion:

1. The chosen shade of ceramic powder was mixed with distilled water on a moist mixing palate and this slurry was applied to the opaque ceramic of the tabs using a brush.
2. The slurry was condensed by hand vibration and then blot dried with absorbent tissue paper. This was repeated until no further water was elicited from the slurries surface.
3. The ceramic tabs were fired in the vacuum porcelain furnace following the manufacturer's instructions and allowed to cool. The furnace reached a maximum temperature of 930°C under vacuum (Appendix A contains full details of the furnace cycle).
4. Additional porcelain, from the same batch, was added to compensate for firing shrinkage. It was condensed and dried as described above and then re-fired using the cycle in Appendix A. This process was repeated up to three times to create tabs of the desired shape and size.
5. The porcelain was ground to give flat surfaces and subsequently polished with polishing stones and wheels.

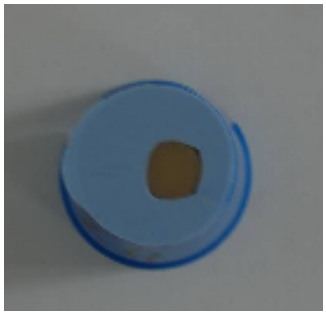
A total of twenty-seven tabs were produced following the procedures above. These consisted of three ceramic thicknesses (1, 1.5 and 2 millimetres) and three tabs of each shade (B1, A3 and D4) for each thickness.

4.2.4 Mounting Procedure for Custom-Made Tabs

A new type of custom holder was needed for this experiment. The tabs were placed

onto a glass slab and their shade and thickness were noted. A polyvinylsiloxane impression material (Aquasil) was mixed according to manufacturer's instructions and placed in a Dappen's Pot. The pot and putty were pressed over a ceramic tab on a glass slab, ensuring the pot was in contact with the glass slab over its whole circumference. The samples and the impression putty were then coated with a precipitated 99% barium sulphate and distilled water paste. The surface of the sample was cleaned, with sterile water, once it was secured in its holder. The samples were mounted in this manner for the remaining experiments. The putty was allowed to set and any excess was removed. All tabs for experiment 4 were made ready for measurement in this manner (Figure 4.6).

Figure 4.6. Custom-made All-Ceramic Tab: Custom Holder for Spectraflash SF600

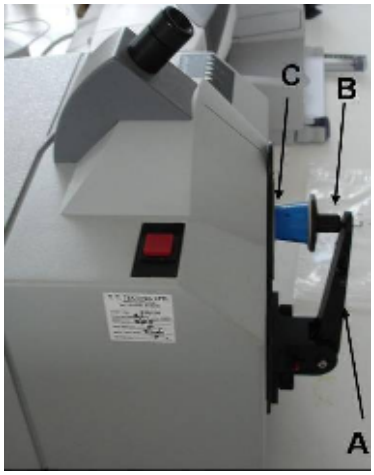


The details of the tab (for example: thickness and shade or surface type and shade) in each pot were recorded and then the pot was assigned a random code. The code and tab details were stored until after all the experimental work was completed. This ensured that the examiner did not know the details of the tab in any particular pot. Analyses of the measurements were completed after revealing the dimensions of each tab.

4.2.5 Measurement Procedure (Colour)

The colour-measuring suite and the settings for the spectrophotometer described in section 4.2.1 were used. The securing arm (A in Figure 4.7) was manipulated until the centre of the tab was in the centre of the measuring aperture. The swivel connector of the securing arm (B in Figure 4.7) prevented any light from escaping between the holder and the aperture (C in Figure 4.7). The author operated this device and each experiment was started and finished in one day. The complete set-up was shown in Figure 4.7.

Figure 4.7. Custom Holder and Spectraflash SF600



Experiment 4A measured the porcelain shade guide tabs used earlier and experiment 4B measured the custom-made all-ceramic tabs of varying thicknesses.

Experiment 4A used one tab of each shade and of both tab surfaces (unaltered and ground) were mounted and measured as previously described.

Experiment 4B used three tabs of each of six thicknesses (1, 1.5, 2, 3, 4 and 5 mm)

of three shades (B1, A3 and D4), producing a total of fifty-four custom-made all-ceramic tabs. Each tab was mounted and measured using the methods described previously.

Experiment 4C used twenty-seven tabs. These consisted of three ceramic thicknesses (1, 1.5 and 2 millimetres) and three tabs of each shade (B1, A3 and D4) for each thickness.

The following measurements of the two different tab types were made:

Experiment 4A: Thirty-one colour measurements of each of the six porcelain shade guide tabs were completed on days 1 and 2.

Experiment 4B: Thirty-one colour measurements of each of the fifty-four custom-made all-ceramic tabs were completed on days 1 and 2.

Experiment 4C: Thirty-one colour measurements of each tab were completed on days 1 and 2.

4.3 The Effects of Metal Treatment and Opaque Ceramic on Spectrophotometric Measurements (Expt.5)

Metal or metal-ceramic tabs removed at various points in the fabrication process were measured. The colour co-ordinates were recorded by the spectrophotometer and were transferred as described previously (section 4.2.1).

4.3.1 Measurement Procedure (Colour)

Nickel-chrome backings and metal-ceramic tabs were removed at various stages in

the fabrication process described in section 4.2.3.2:

1. Three nickel-chrome backings after sandblasting
2. Three nickel-chrome backings after sandblasting and steam cleaning
3. Three nickel-chrome backings after sandblasting, steam cleaning and oxidisation
4. Three tabs were removed after firing the Vita VMK 95 wash opaque porcelain
5. Nine tabs were coated with shade designated Vita VMK 95 paste opaque porcelain, three of each shade (B1, A3 & D4).

This provided twenty-one tabs comprising five different types which were stored in sealed containers until colour measurement.

Experiment 5: Thirty-one colour measurements of each tab were completed on days 1 and 2.

4.4 The Effects of the Number of Ceramic Firings on Spectrophotometric Measurements (Expt. 6)

Metal-ceramic tabs fabricated following a varied number of cycles were measured. The colour co-ordinates were recorded by the spectrophotometer and were transferred as described previously (section 4.2.1).

4.4.1 Measurement Procedure (Colour)

The ceramic was added by the method in section 4.2.3.2 but the number of ceramic

firings was varied. Samples of two millimetre thickness, of each shade, were fabricated either being fired two, three or four times. This provided a total of eighteen metal-ceramic samples as two tabs of each group were prepared.

Experiment 6A: The tabs were measured thirty-one times on days 1 and 2.

The coefficients of variation were calculated for expt. 6A: the B1 tabs that had been fired four times had a* values with coefficients >1%, however the actual differences were very small (≤0.02 units). The largest difference across the shades was 0.22 units (b* - shade D4) which was larger than the acceptable level for one colour co-ordinate (Table 2). When tabs that were fired twice were considered, there was drifting of the measurements from the Spectraflash to a larger degree than previously seen (Table 2).

Table 2 Instrument drift from Expt. 6A (Shade D4 – 2 firings)

	L*	a*	b*	L*	a*	b*	L*	a*	b*	L*	a*	b*
	Tab1: Day 1			Tab1: Day 2			Tab2: Day 1			Tab2: Day 2		
Maximum	69.11	2.15	17.85	69.39	2.10	17.98	68.95	2.09	17.69	69.19	2.15	17.16
Minimum	69.03	2.13	17.71	69.30	2.08	17.88	68.88	2.07	17.55	69.08	2.13	16.94
Coefficient of Variation	0.03%	0.29%	0.28%	0.03%	0.26%	0.18%	0.03%	0.25%	0.20%	0.04%	0.28%	0.34%

Table 3 Instrument drift from Expt. 6B (Shade D4 – 2 firings)

	L*	a*	b*	L*	a*	b*	L*	a*	b*	L*	a*	b*	L*	a*	b*	L*	a*	b*
	Tab1: Day 1			Tab1: Day 2			Tab2: Day 1			Tab2: Day 2			Tab3: Day 1			Tab3: Day 2		
Original																		
Maximum	69.19	1.99	17.97	69.71	2.14	17.76	69.82	2.09	18.01	69.71	2.14	17.76	69.42	2.08	17.91	69.54	2.13	17.87
Minimum	69.19	1.98	17.95	69.70	2.12	17.74	69.81	2.08	17.97	69.70	2.12	17.74	69.42	2.06	17.88	69.53	2.12	17.84
Coefficient of Variation	0.00%	0.17%	0.04%	0.00%	0.27%	0.04%	0.01%	0.17%	0.06%	0.00%	0.27%	0.04%	0.00%	0.27%	0.05%	0.01%	0.21%	0.04%
New																		
Maximum	69.68	2.12	17.69	69.65	2.23	17.76	69.66	1.91	17.27	69.51	1.89	17.11	69.92	1.84	17.1	69.89	1.8	16.95
Minimum	69.66	2.11	17.66	69.63	2.22	17.72	69.64	1.9	17.23	69.5	1.87	17.08	69.91	1.82	17.07	69.88	1.78	16.92
Coefficient of Variation	0.01%	0.24%	0.05%	0.01%	0.23%	0.04%	0.01%	0.24%	0.06%	0.01%	0.27%	0.04%	0.01%	0.23%	0.04%	0.01%	0.28%	0.05%

The changes were small, however a sequential movement was seen across each full data set. The L* values increased (by between 0.07 to 0.11 units), a* values showed little variation (0.02 units) while b* values decreased (range 0.10 to 0.22). Following analysis of the results the shade D4 tabs were re-made and re-measured, as increased instrument drift was identified: 6 D4 Vita (Vita-Zahnfabrik) VMK 95 dentine ceramic tabs 2 mm thick were fabricated, mounted and measured in the same manner described above. Three tabs were fabricated of shade D4 ceramic from the same Vita ® VMK 95 opaque, shade opaque and dentine ceramic batches as experiment 6A. A further three tabs were fabricated from the same Vita ® VMK 95 opaque and shade opaque ceramic bottles but a different shade D4 dentine ceramic batch. All the samples were sintered using only two dentine firing cycles (Appendix A).

Experiment 6B: The six tabs were measured thirty-one times on days 1 and 2.

Six new tabs of the same shade D4 were fabricated (experiment 6B) using the previous body ceramic powder and also a new batch of body ceramic powder. The opaque ceramics used were of the same batch as used previously.

The coefficient of variation was ≤0.28% and the maximum variation was 0.04 units in expt. 6B (Table 3). These were more harmonious with the results from previous experiments. Instrument drift appeared to be transient which might have been related to an unidentified environmental problem on the day of measurement or possibly instrument drift following extensive use. The reason for this drift was unknown and was extremely small. In order to minimise drift, the spectrophotometer was allowed to ‘rest’ for 15 minutes for every 3 hours during further experiments and as can be seen from Table 3 drift was reduced back to within normal limits and the

full data set was recorded in Appendix D. Subsequent experiments did not exhibit drift. However, no recommendations could be located in the literature to support or refute this protocol.

4.5 The Effects of the Operator on Spectrophotometric Measurements of Metal-Ceramic Samples (Expt. 7)

Metal-ceramic tabs fabricated by different ceramists were measured. The colour co-ordinates were recorded by the spectrophotometer and were transferred as described previously (section 4.2.1).

4.5.1 Measurement Procedure

The investigator produced five shade A3 tabs with a total ceramic thickness of 2 mm using the methods described above. In addition, five nickel-chrome backings with both types of opaque ceramic fired onto them were fabricated. The tabs were then given to an experienced dental ceramist who added body ceramic in accordance with the protocol (section 4.2.3.2) to provide a total ceramic thickness of 2 mm. These samples had the body ceramic fired twice during their fabrication in the same furnace on the same settings as used previously.

Experiment 7A: The investigator's five tabs were measured thirty-one times.

Experiment 7B: The ceramist's five tabs were measured thirty-one times

4.6 The Effects of Varying Ceramic Condensation on Spectrophotometric Measurements (Expt. 8)

Metal-ceramic tabs were measured where four different methods of porcelain condensation were used. The colour co-ordinates were recorded by the spectrophotometer and were transferred as described earlier (section 4.2.1).

4.6.1 Metal-Ceramic Samples

Samples of 2 mm ceramic thickness were fabricated and mounted as described previously with the following alterations:

1. The dentine ceramic of the metal-ceramic samples were fired twice.
2. The furnace used in the previous experiments became unusable: this was replaced by a second furnace which was the same model as the original. The cycles described previously were used.
3. During mounting, the centre of the area measured by the spectrophotometer was marked after the colour co-ordinates had been recorded.
4. Several methods were used to condense the ceramic slurry and these are described below:

4.6.1.1 Methods of Ceramic Condensation

The ceramic slurry (section 4.2.3.2) was condensed using one of these four methods:

A. The slurry was applied to the metal backing and gently blot dried for 90 seconds with absorbent tissue paper. These tabs constituted Group A.
B. The method of condensation described in section 4.2.3.2. was used which

involved hand vibration with an instrument and blot drying. These tabs were labelled Group B.

C. A Shofu ® (Shofu Corporation, Kent, United Kingdom) Ceramosonic II Condenser PN5062 was used. The slurry was condensed on this machine and any excess water removed by blotting with a tissue. This was repeated until no further water could be elicited. The condenser had its operating frequency set to 27,000 Hertz for the duration of the experiment. The tabs were labelled Group C.

D. The slurry was placed onto a metal backing, briefly dried with a tissue and additional ceramic powder of the appropriate shade was added until no further powder was absorbed. These tabs constituted Group D.

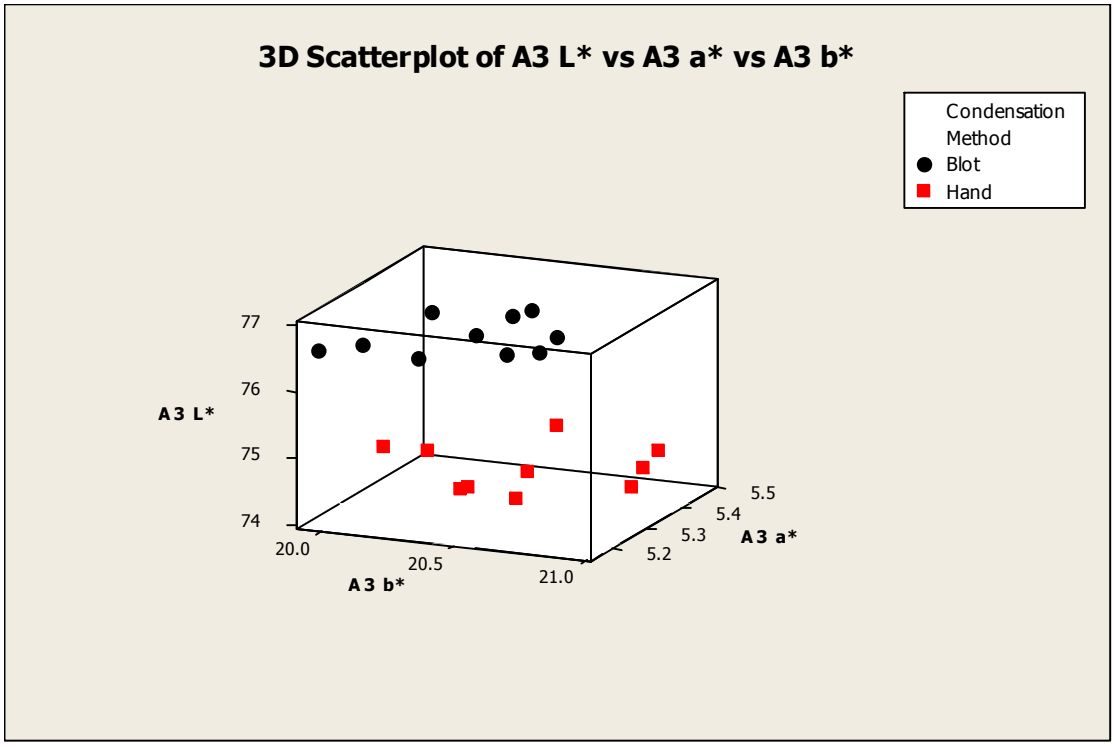
4.6.2 Measurement Procedure (Colour)

Custom-made metal-ceramic samples were fabricated by different modes of ceramic condensation were measured by the Spectraflash SF600. It was not known if this would have any effect on the colour co-ordinates and therefore pilot investigations were required:

4.6.2.1 Pilot Investigations

Ten tabs from groups A and B were fabricated of shade A3 ceramic and all were measured 31 times by the spectrophotometer. The results shown below (Figure 4.8) demonstrated a difference between the colour co-ordinates of the groups. The mean colour co-ordinates, standard deviations and coefficient of variations were placed in Appendix E.

Figure 4.8. L*a*b* Colour Co-ordinates for the First Pilot Study using Group A and B tabs (Shade A3)



The colour difference between the tab groups were shown in Table 4:

Table 4 First Pilot Study: Differences in Colour Between Group A and B Tabs

	ΔL*	Δa*	Δb*	ΔE
A v B	-1.92	0.02	0.20	**1.40**

Following pilot study 1, a second preliminary study was completed, using five tabs of each of the four tab groups. Each tab was measured 31 times by the spectrophotometer. Figure 4.9 showed large differences in colour co-ordinates across the tab groups, these were demonstrated in Table 5. The mean colour co-ordinates, standard deviations and coefficient of variations were placed in Appendix

F.

Figure 4.9. L*a*b* Colour Co-ordinates for the Second Pilot Study using All Tab Groups (Shade A3)

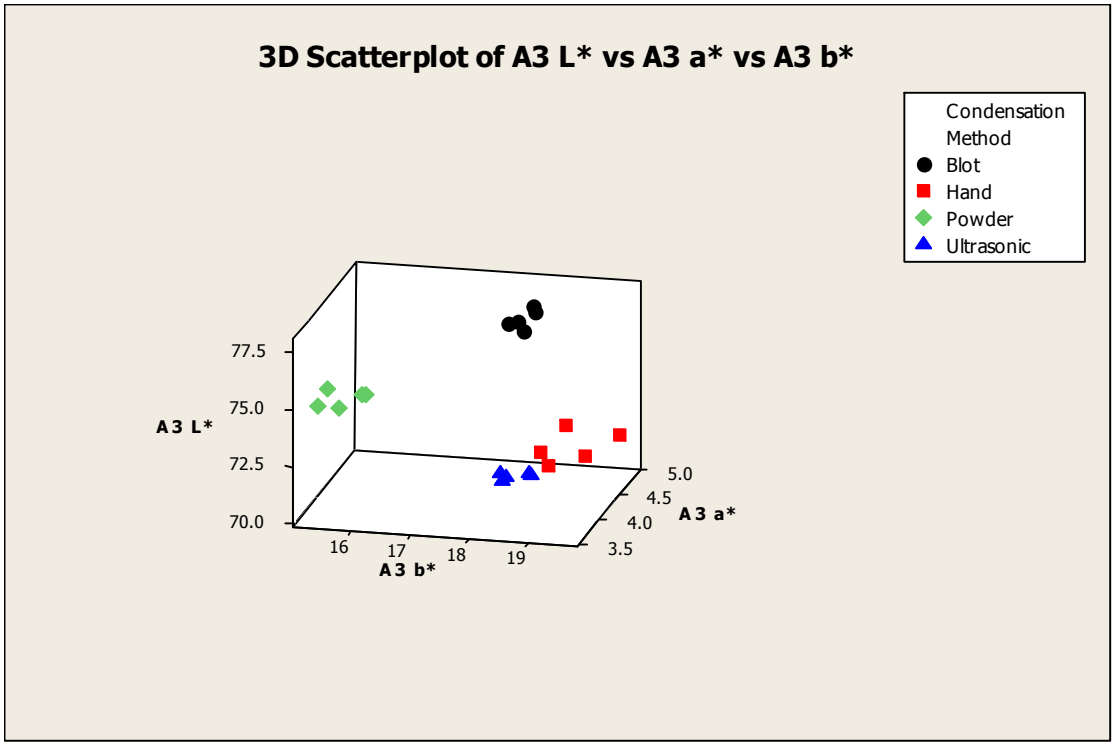


Table 5 Second Pilot Study: Differences in Colour Between the Tab Groups A, B, C and D

	ΔL*	Δa*	Δb*	ΔE
A v B	-5.67	-0.02	0.68	**4.17**
A v C	-6.95	-0.11	-0.15	**5.13**
A v D	-2.79	-0.73	-2.63	**2.55**
B v C	-1.28	-0.09	-0.83	**1.08**
B v D	2.88	-0.72	-3.31	**2.87**
C v D	4.16	-0.62	-2.48	**3.45**

It was observed the method of ceramic condensation definitely had an effect on the colour co-ordinates of metal-ceramic samples. It was decided to increase both the number of samples and shades tested:

4.6.2.2 Experiment 8

Ten tabs of each group (A, B, C and D) were fabricated. Shades B1, A3 and D4 of Vita VMK 95 ceramic were chosen producing one-hundred and twenty metal-ceramic samples.

Experiment 8: All tabs were measured 31 times by the spectrophotometer.

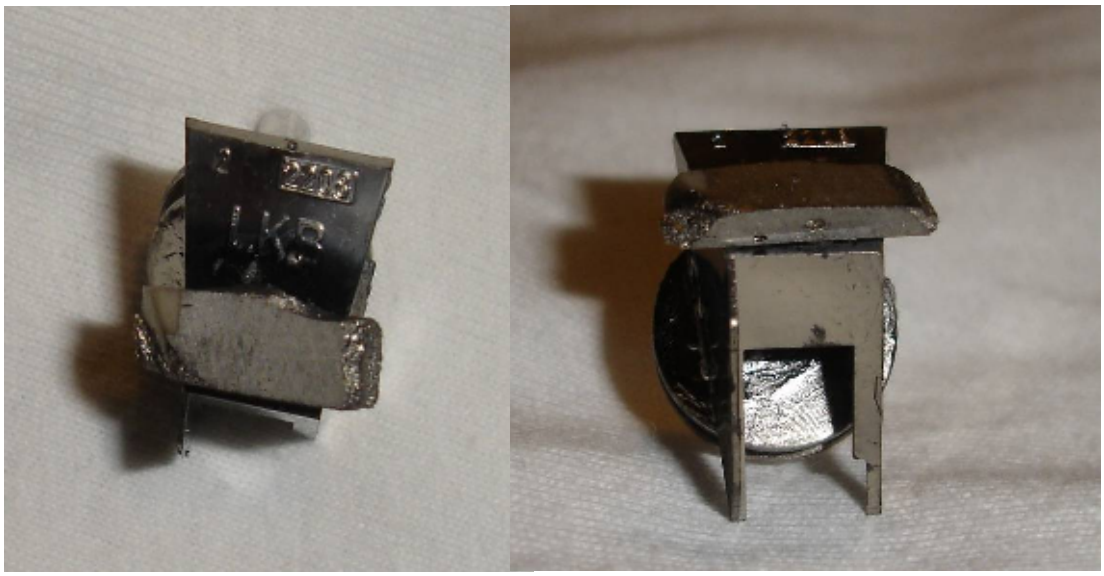
4.7 The Effect of Varying Ceramic Condensation on Porosity (Expt. 9)

The porosity of the metal-ceramic samples in each condensation group was determined.

4.7.1 Scanning Electron Microscope

The sectioned samples were mounted on aluminium stubs with carbon cement and coated with gold in a sputter coater. Coated samples were shown in Figure 4.10.

Figure 4.10. Custom holder for SEM



The samples were viewed in a Scanning Electron Microscope (S.E.M.) Figure 4.11) with the samples mounted at a 15 degree viewing angle. The areas that were analysed by a spectrophotometer in experiment 8 were located on the specimens and photomicrographs were exposed of the sub-surface areas at these locations. In addition, a photomicrograph was taken at the location measured by the spectrophotometer on the polished, top surface of the tabs in experiment 8. All photomicrographs were exposed at 600x magnification using photographic film with a scale bar along their lower border which indicated the actual length of the samples.

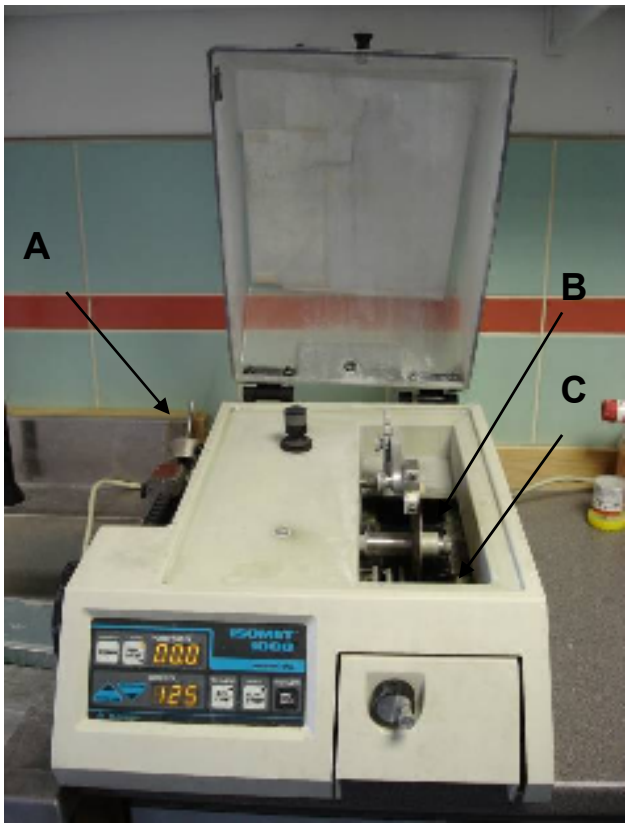
Figure 4.11. SEM

4.7.2 Sectioning and Polishing of Metal-Ceramic Samples

All samples were sectioned using a Buehler Isomet 1000 saw (Figure 4.12) at 125 revolutions per minute with its 200 gram weight on its cutting arm (A in Figure 4.12).

The samples were held beneath the diamond wafering blade, (B in Figure 4.12) using the securing arm. The Buehler cutting fluid was placed in the bath of the cutter (C in Figure 4.12) with a lubricant to water ratio of 1:9. The sectioned samples were rinsed with water and cleaned using a lint-free cloth.

Figure 4.12. Isomet 1000 Saw



The code of each tab from experiment 8 was transcribed from their custom holder onto both halves of the sectioned tabs on the metal surfaces. Only one half of each sectioned tab was analysed as some sectioned tabs fractured during the sectioning and SEM procedures.

4.7.3 Image Analysis

The images from section 4.7.1 were processed and hard copies produced. A scanner was calibrated according to the manufacturer's instructions. The photomicrographs were scanned and saved, with no compression, as Joint Photographic Experts Group (JPEG) images. The scanned images were then analysed using a digital software package.

The JPEG images were imported into image analysis software. After visual inspection and digital calibration of the images to ensure the images were of the same brightness, a pixel RGB value of less than 50 was decided as the limit that indicated a pore. All images were then:

- cropped to the same dimensions
- calibrated to enable length measurements and area calculations

The method described by Geirsson et al (2004) was used to calculate the porosity of the ceramic. A macro was set up in Image J to make the image binary with a threshold of 50 (RGB value) which made all pixels equal to and above 50 white and all those below black. A second macro placed a grid template (10 squares by 10 squares) over each image. Each intersection could be magnified to identify pores. These intersections were examined and the number containing a pore was counted.

In addition to the point counting method, an Image Analysis Technique was used in experiment 9. Each image was cropped away from the image margins and the scale bars. The percentage of each image with an RGB value of less than 50 was calculated by the software.

4.7.3.1 Data Transfer and Calculations for Experiment 9

The data was inputted directly into spreadsheets, for the point counting method or were transferred there from the Image J output after using the image analysis technique.

1. The mean pore counts and porosity percentages were calculated for each tab.
2. The standard deviations around these mean values were calculated for each data set.

4.7.4 Measurement Procedure (Porosity)

The metal-ceramic tabs from the pilot investigations and experiment 8 were used in experiment 9. The sectioned samples were prepared, encrypted and photographed as described previously.

4.7.4.1 Pilot Investigations

The ten tabs from groups A and B, used in the first pilot study of experiment 8, were examined. The porosity of these twenty tabs was assessed by the pointing counting method on both days 1 and 2.

The results showed that there was a difference in the pore counts of the two groups. Group A tabs had a mean count of 10.80 (+/-3.19) compared to 5.10 (+/-1.20) for the group B tabs. Both tab groups had a Cohen's Kappa coefficient of 1.

Following this preliminary investigation, a second pilot study was completed using the 20 tabs from the second pilot study in experiment 8. The porosity of these tabs was assessed by the pointing counting method on both days 1 and 2. The following results were recorded:

- Group A: 10.90 (+/-3.07)

- Group B: 4.40 (+/-0.84)
- Group C: 3.10 (+/-1.20)
- Group D: 7.30 (+/-2.50)

The Cohen's Kappa coefficients were equal to 1 for tab groups A, B and D. Group C tabs had one tab in which the pore count was different by 1 pore, giving a Kappa value of 0.87. There were no statistical differences in the number of pores from groups A and B between the pilot investigations. It was therefore concluded that each method of ceramic condensation removed a relatively consistent amount of water from the slurry and also that point counting method was reliable.

4.7.4.2 Experiment 9: Protocol

The porosity of the one hundred and twenty tabs from experiment 8 was assessed by both the pointing counting method and the Image Analysis Technique described previously (section 4.7.3).

Experiment 9: The microscopic properties of the tabs were analysed.

4.8 Statistical Analysis

The statistical tests used were one-way Analysis of Variance (ANOVAs), coefficient of variation, linear regression analysis and Cohen's Kappa Coefficient.

ANOVA testing produced analysis of variance tables with individual 95% confidence intervals (C.I.) for the means that were based on the pooled standard deviation. 95%

C.I.'s were used unless otherwise stated.

Linear regression produced R-Sq values, which indicated the strength of the relationship, and was expressed as a percentage of the square of the correlation value. The slope of the graph was used to indicate the direction of the association.

The Coefficient of Variation (%) was calculated for every reading for each colour co-ordinate component in the data set by the following formula:

100*(Standard Deviation)/(mean value of set)

Where the *standard deviation* was the square root of the sum of $\{(x - \text{mean})^2 / (n-1)\}$. Where, *x* was the data's value, *mean* was the arithmetic mean of the data items and *n* was the number of data items (n was equal to 30 in all experiments in this thesis).

Cohen's Kappa Coefficient was used as a measure of the intra-rater reliability when counting the number of pores in experiment 9.

CHAPTER 5: RESULTS

The complete data sets and some summary data were omitted, only the pertinent summary data was presented in this chapter. However, the complete data sets are found on the attached CD and are numbered according to the table number in this chapter. In addition, the Figures that are 3D charts are also on the CD where they can be manipulated in three-dimensions.

A number of types of colour difference was calculated:

1. Δe*:* when the coefficient of variation was greater than 1% the calculations described in section 4.1.1.1 were used. Briefly, the mean of each data set was calculated and then the colour difference between each individual reading and this mean was calculated, giving thirty colour differences. The mean and SD of these thirty differences were then calculated and displayed under the Δe heading. These calculations were only made in experiments 1 through 3.
2. ΔE: Colour differences were calculated between the means of the data sets and the results presented under the ΔE in experiments 1 to 3.
3. ΔE_{00}: Colour differences were calculated between the means of the data sets and the results presented under the ΔE in all remaining experiments.

The distinction between ΔE and ΔE_{00} was made because of the different colour scales used by IdentaColor II (ΔE) and SpectraFlash (ΔE_{00}).

5.1 Microspectrometer (IdentaColor II) Measurement of Porcelain Samples

Summary data for experiments 1 to 3 regarding the repeatability (Table 13) and the colour differences (ΔE) between the unaltered and ground tabs (Table 14) were recorded in sections 5.1.4 and 5.1.5 respectively.

5.1.1 Effect of Re-Calibration using IdentaColor II (Expt. 1)

The device was calibrated at the start of each measurement session and then two different protocols were followed: (A) when the device requested re-calibration and (B) re-calibration after every measurement. Table 6 and Figure 5.1 indicated that slight differences in the α, β and γ values of the two re-calibration methods were present but these were extremely small. It was unknown which re-calibration method was closer to the 'true' colour of the tab or if the inherent day-to-day variability of spectrophotometers accounted for most of this difference.

For unaltered tabs, the ΔE from the data in Table 6 was 0.61, mainly due to changes in the α and γ values. The tabs measured when recalibrating after every measurement had smaller α values (≈0.6 units) and higher γ values (≈0.7 units), these were both significantly different ($p<0.001$), indicating that they were darker and more yellow. No statistical difference was found for the β values ($p>0.05$).

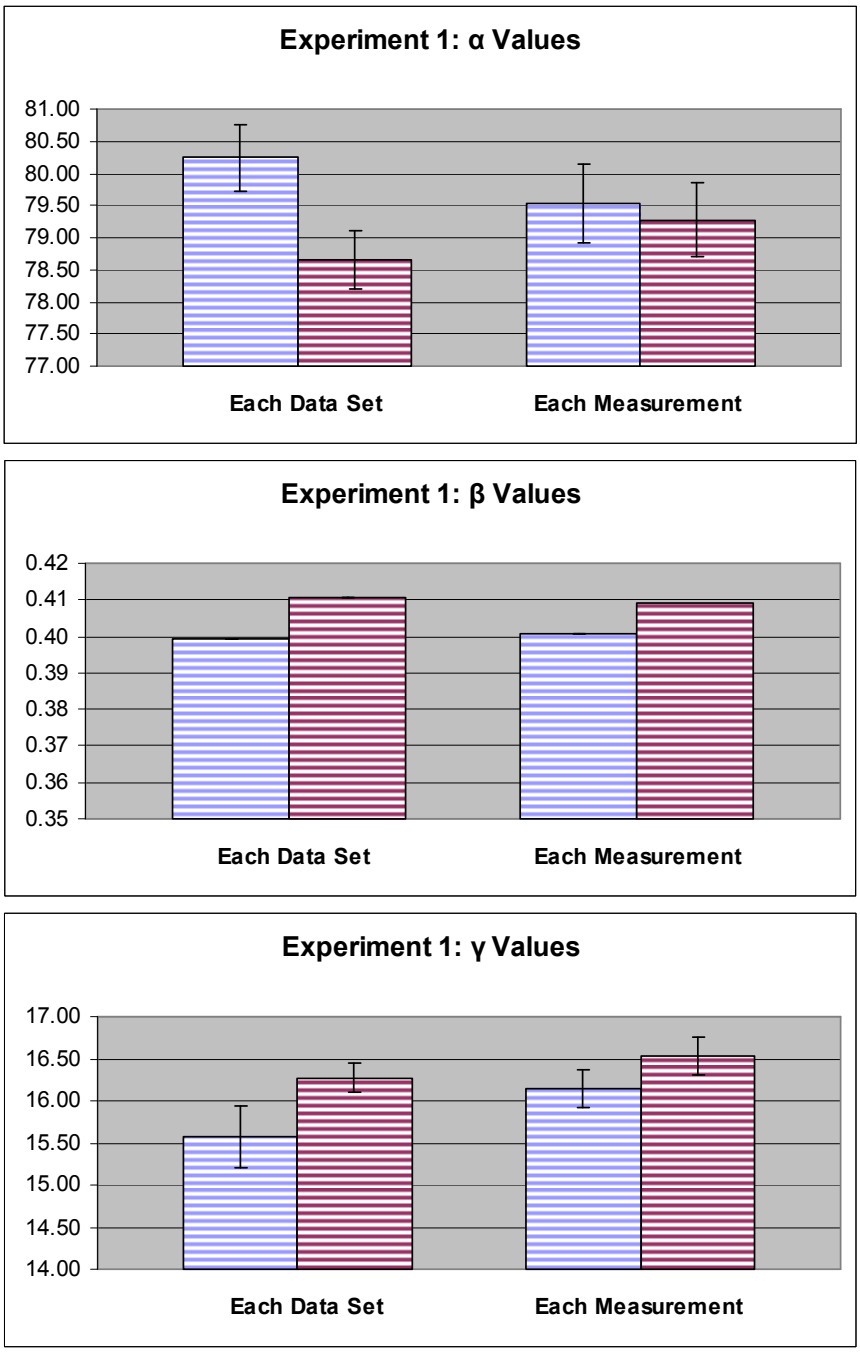
For ground tabs, the ΔE from the data in Table 6 was 0.45. The tabs measured when recalibrating after every measurement had larger α values (≈0.6 units) and again had larger γ values (≈0.3 units), these were significantly different ($p<0.05$). There was only 0.01 units between the mean of the β values. This indicated that

they were lighter and more yellow.

Table 6 Effects of Calibration Method on Mean Colour Values (α, β and γ), Standard Deviations (SD) and Coefficients of Variation % (CV)

		α			β			γ		
		Mean	**SD**	**CV**	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**
Calibration before each data set	*Unaltered A3 tab*	**80.25**	0.52	0.64%	**0.40**	0.00	0.91%	**15.57**	0.36	2.34%
	Ground A3 tab	**78.66**	0.45	0.57%	**0.41**	0.00	0.62%	**16.27**	0.17	1.06%
Calibration after each measurement	*Unaltered A3 tab*	**79.52**	0.57	0.72%	**0.40**	0.00	0.91%	**16.14**	0.22	1.33%
	Ground A3 tab	**79.27**	0.61	0.77%	**0.41**	0.00	0.75%	**16.53**	0.23	1.38%

Figure 5.1. Mean Colour Values of Proprietary Unaltered and Ground Tabs (Shade A3) using both Methods of Calibration



The scales used in the bar charts were not the same.

5.1.2 Effect of Lighting Conditions using IdentaColor II (Expt. 2)

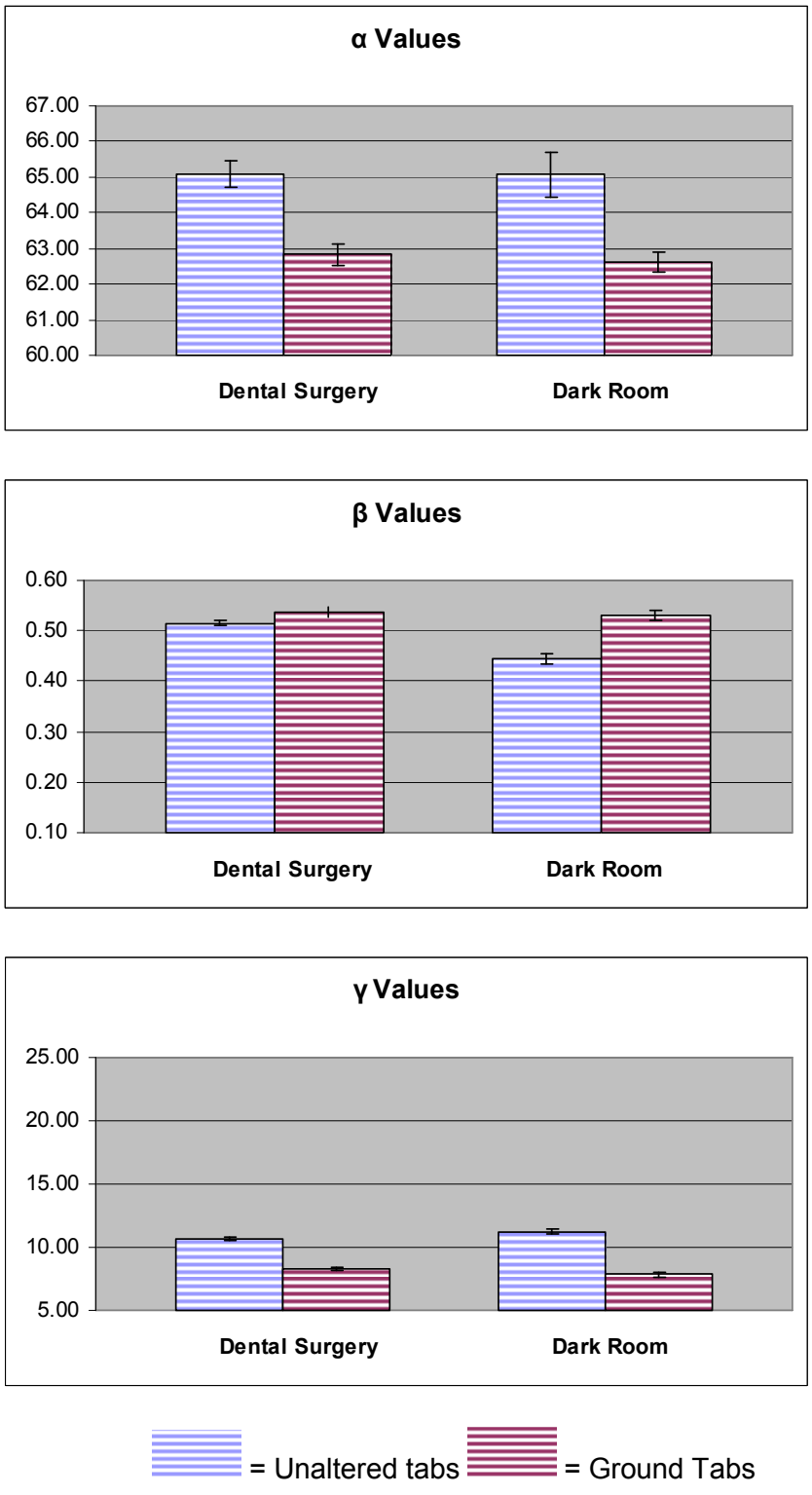
The light source of the device and the ambient lighting could have affected colour measurements. This experiment assessed the effect of clinical lighting on the colour measurements made by IdentaColor II.

Table 7 and Figure 5.2 recorded that the α, β and γ values changed when the two different lighting conditions were compared. However, no absolute correlations between lighting environments were seen: both the α and γ values varied for both tab surfaces but not in a consistent direction.

Table 7 Effect of Lighting on Mean Colour Values (α, β and γ), Standard Deviations (SD) and Coefficients of Variation % (CV)

			α			β			γ		
			Mean	**SD**	**CV**	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**
B1	**Dental Surgery**	*UNALTERED TAB*	**104.14**	0.95	0.91%	**0.28**	0.00	0.91%	**21.68**	0.23	1.06%
		GROUND TAB	**103.65**	1.31	1.27%	**0.29**	0.01	2.00%	**20.25**	0.28	1.36%
	Dark Room	*UNALTERED TAB*	**104.81**	1.09	1.04%	**0.27**	0.01	1.85%	**22.27**	0.23	1.01%
		GROUND TAB	**103.62**	0.91	0.88%	**0.28**	0.00	1.44%	**19.54**	0.26	1.32%
A3	**Dental Surgery**	*UNALTERED TAB*	**79.77**	0.39	0.49%	**0.40**	0.00	1.04%	**16.34**	0.13	0.82%
		GROUND TAB	**79.75**	0.54	0.67%	**0.41**	0.00	1.15%	**16.90**	0.17	1.03%
	Dark Room	*UNALTERED TAB*	**79.01**	0.38	0.48%	**0.41**	0.00	1.23%	**16.28**	0.18	1.11%
		GROUND TAB	**78.73**	0.32	0.41%	**0.41**	0.00	1.13%	**16.68**	0.21	1.26%
D4	**Dental Surgery**	*UNALTERED TAB*	**65.45**	0.36	0.56%	**0.52**	0.01	0.99%	**10.67**	0.14	1.29%
		GROUND TAB	**62.84**	0.31	0.49%	**0.54**	0.00	0.91%	**8.29**	0.12	1.43%
	Dark Room	*UNALTERED TAB*	**65.08**	0.64	0.99%	**0.44**	0.01	1.53%	**11.25**	0.51	4.51%
		GROUND TAB	**62.60**	0.29	0.46%	**0.53**	0.00	0.48%	**7.88**	0.20	2.57%

Figure 5.2. Influence of Lighting Conditions on Mean Colour Values (±SD) Proprietary Unaltered and Ground Tabs (Shade D4)



The data of the shade D4 tabs were shown as they were representative of the samples in this experiment. The scales used in the bar charts were not the same.

Statistical analysis generally revealed significant differences between the α, β and γ values from the dental surgery and the dark room (both tab surfaces). There were two exceptions, the ground B1 α value ($p>0.05$) and A3 γ value ($p>0.05$).

Table 8 Differences in ΔE, using Mean Colour Values, between Lighting Conditions

Unaltered Tabs		Δα	Δβ	Δγ	ΔE
B1		0.67	0.00	0.58	**0.47**
A3		-0.76	0.01	-0.06	**0.53**
D4		-0.37	-0.08	0.58	**0.51**
Ground Tabs					
B1		0.04	0.00	-0.73	**0.39**
A3		-1.01	0.01	-0.23	**0.72**
D4		-0.24	-0.01	-0.41	**0.36**

Table 8 recorded the colour differences (ΔE) between the colour values from both lighting conditions. The unaltered tabs had small differences between the mean values of 0.47, 0.53 and 0.51 units for shades B1, A3 and D4 respectively. The ground tabs had larger colour differences for A3 tabs (0.72 units) but smaller ones for B1 (0.39) and D4 (0.36) compared to the unaltered tabs. These differences between the colour values recorded under the two lighting conditions were small. However, several would have been discernible under ideal viewing conditions. The inherent day-to-day variability of spectrophotometers might also have contributed to the colour differences, however, the true accuracy of these conclusions can again be questioned due to the colour scale used by IdentaColor II. It cannot be determined which lighting condition was most accurate as no colour standard was available for comparison. Dark room conditions were therefore not used for subsequent experiments as the repeatability was not reduced by dental surgery lighting.

5.1.3 Effect of Time using IdentaColor II (Expt. 3)

Experiment 3 tested the repeatability and reproducibility of IdentaColor II in measuring:

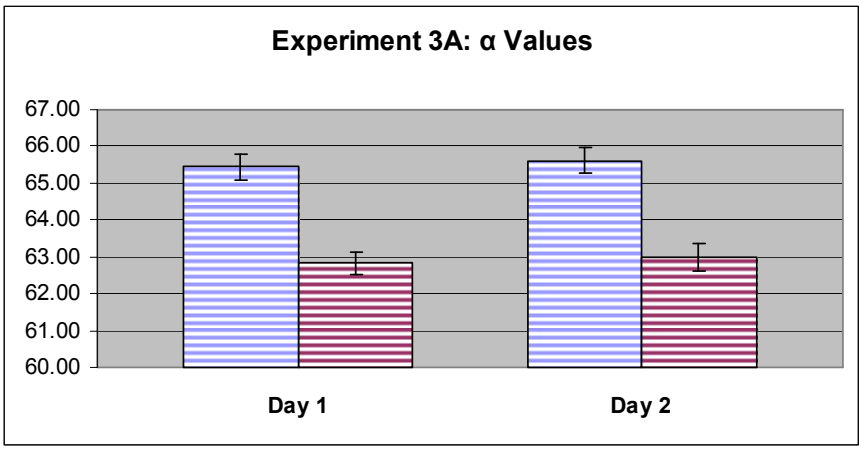
- The colour values of three shades of propriety, porcelain shade guide tabs (Experiment 3A)
- The shade selections of these shade guide tabs (Experiment 3B)
- The shade selections of all-ceramic samples of 1, 2, 3, 4, and 5 mm thickness (Experiment 3C)

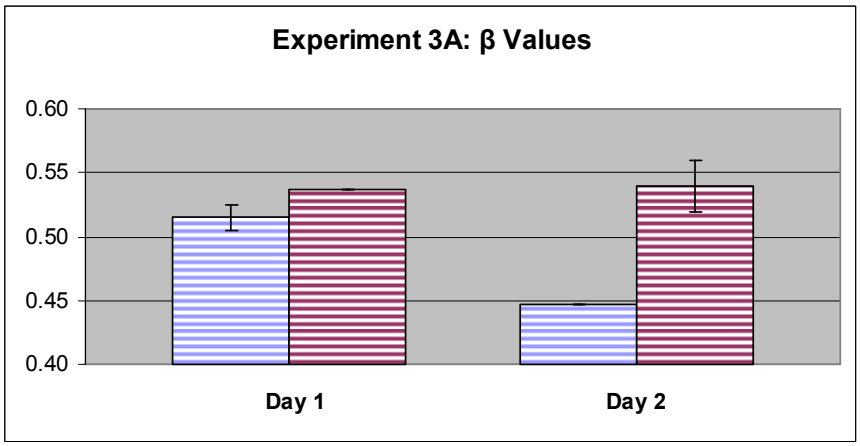
Experiment 3A and 3B had to be two separate experiments because IdentaColor II could not record the shade and colour values at the same time.

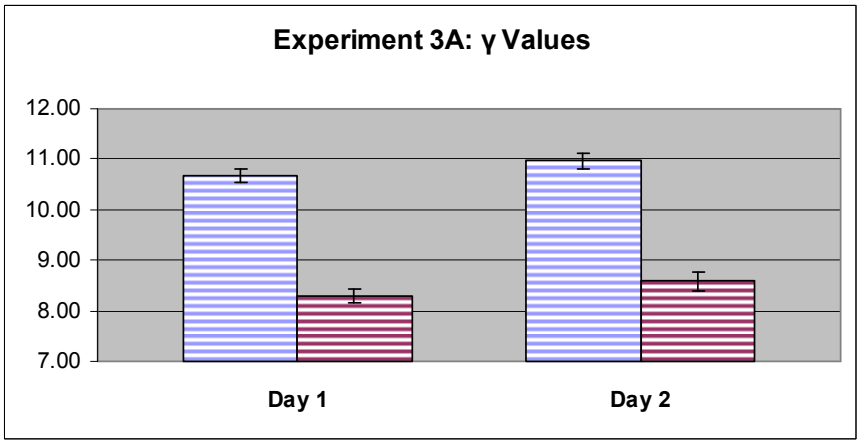
Differences in Colour Values between the Same Proprietary Tabs Recorded on Different Days (Expt. 3A)

Figure 5.3 and Table 9 recorded the changes in α, β and γ whilst Table 10 recorded the colour differences (ΔE) between days 1 and 2. Only the unaltered B1 tabs had a difference (0.52) greater than the perceptibility threshold of 0.4 units. There were slight differences between the mean α, β and γ values for each shade tab, however the α values had the largest changes (up to 0.94 units), although IdentaColor II's larger scale may again have influenced these.

Figure 5.3. Influence of Time on Mean Colour Values (±SD) of Proprietary Unaltered and Ground Tabs (Shade D4)







= Unaltered tabs = Ground Tabs

The day 1 bar charts of α, β and γ values of shade D4 tabs were shown as they were representative of the samples. The scales used in the bar charts were not the same.

Table 9 Effect of Tab Surface (Unaltered and Ground) on Mean Colour Values (α, β and γ), Standard Deviations (±SD) and Coefficients of Variation % (CV)

			α			β			γ		
			Mean	**SD**	**CV**	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**
B1	Day 1	*UNALTERED TAB*	**104.14**	0.95	0.91%	**0.28**	0.00	0.91%	**21.68**	0.23	1.06%
		GROUND TAB	**103.65**	1.31	1.27%	**0.29**	0.01	2.00%	**20.25**	0.28	1.36%
	Day 2	*UNALTERED TAB*	**105.08**	0.96	0.92%	**0.28**	0.00	1.73%	**21.58**	0.23	1.05%
		GROUND TAB	**103.34**	0.77	0.74%	**0.29**	0.01	2.01%	**20.29**	0.20	1.00%
A3	Day 1	*UNALTERED TAB*	**79.77**	0.39	0.49%	**0.40**	0.00	1.04%	**16.34**	0.13	0.82%
		GROUND TAB	**79.75**	0.54	0.67%	**0.41**	0.00	1.15%	**16.90**	0.17	1.03%
	Day 2	*UNALTERED TAB*	**79.46**	0.29	0.36%	**0.40**	0.00	1.16%	**16.29**	0.17	1.02%
		GROUND TAB	**79.75**	0.30	0.37%	**0.41**	0.00	1.10%	**16.86**	0.19	1.12%
D4	Day 1	*UNALTERED TAB*	**65.45**	0.36	0.56%	**0.52**	0.01	0.99%	**10.67**	0.14	1.29%
		GROUND TAB	**62.84**	0.31	0.49%	**0.54**	0.00	0.91%	**8.29**	0.12	1.43%
	Day 2	*UNALTERED TAB*	**65.62**	0.35	0.53%	**0.45**	0.00	1.04%	**10.97**	0.16	1.47%
		GROUND TAB	**62.99**	0.38	0.60%	**0.54**	0.02	2.90%	**8.59**	0.19	2.26%

Table 10 Differences in ΔE between Days 1 and 2 for Three Shades of Proprietary Tab, using Mean Colour Values

Unaltered Tabs		**Δα**	**Δβ**	**Δγ**	**ΔE**
B1		0.94	0.00	-0.10	**0.52**
A3		-0.31	0.00	-0.05	**0.22**
D4		0.17	-0.07	0.30	**0.27**
Ground Tabs					
B1		-0.31	0.00	0.04	**0.17**
A3		0.00	0.00	-0.04	**0.02**
D4		0.15	0.00	0.30	**0.25**

It was concluded that the colour values from IdentaColor II were not from a C.I.E. scale as some L* values were above 100. Values of this magnitude indicated a fluorescent sample which the B1 tabs clearly were not. In addition, the range of α

and γ indicated that these tabs covered a larger area of this colour space than the literature indicated. Experiments 3B and 3C therefore recorded the shade determined by IdentaColor II.

Shade Selections of the Same Proprietary Tabs Recorded on Different Days (Expt. 3B)

The number of times that the most frequently selected shade (mode) was selected from the thirty determinations was recorded. The device consistently recorded the conventional shade designation of both the unaltered and ground proprietary tabs. On both days 1 and 2 the same shade was selected for each tab, although the frequency with which it was selected varied slightly (Table 11). The alternate shade selections were recorded in Appendix T.

Table 11 IdentaColor II Most Frequently Selected Shades for Proprietary Shade Tabs

	Unaltered Tabs					
	Day 1			**Day 2**		
Tab Designation	B1	A3	D4	B1	A3	D4
Most Frequent Shade	A1	A2.5	C3.5	A1	A2.5	C3.5
No.of Times Selected	30	30	30	29	30	30
	Ground Tabs					
	Day 1			**Day 2**		
Tab Designation	B1	A3	D4	B1	A3	D4
Most Frequent Shade	A1.25	B2.5	A4	A1.25	B2.5	A4
No.of Times Selected	30	30	30	29	30	30

More importantly, the shade selected by IdentaColor II did not match the shade designation of the tab. Slight variation in probe positioning would not have

influenced the results as the majority of the results were identical over time unless the area measured was not representative of the tab. A small surge or drop in electricity could have accounted for the occasional change in shade selection in each data set as the current was not fully regulated, but not the differences between the shade designation of the tab and the shade IdentaColor selected.

Shade Selections of Custom-made Tabs (Expt. 3C)

The mode of the shade selections were recorded in Table 12 as well as the number of times this was chosen. The all-ceramic samples showed good reproducibility between days 1 and 2. As thickness increased the variation in shade between different days decreased, 26 of the 45 tabs (57%) had no change from day 1 to 2. 78% of the 1 mm tabs had differences between days compared with only 22% of the 5 mm tabs. 75% (9 of 12) of the B1 tabs, 42% (5 of 12) of the A3 tabs and 42% (5 of 12) of the D4 tabs had slight differences in the shade selected on days 1 and 2. In addition, the 1 mm D4 tab was recorded as being 0.5 shade units darker on day 2 (B3 to B3.5) in every measurement. Small fluctuations within the data sets were similar to those observed with the proprietary shade tabs. The device was repeatable when measuring all-ceramic tabs within each data set. However, thinner tabs and those of B1 had reduced repeatability.

Table 12 recorded that the shade selection changed, for shade B1 and A3 tabs, between the 1 and 3 mm tabs and then usually remained constant. For example, the shade selection for the 1 mm B1 tab was B2.5, the 2 mm tabs was A1.5 and the remaining tabs were approximately A1.25. This indicated that the colour values changed as the thickness increased up to 3 mm and thereafter no clinically relevant changes occurred. This might have been due to increased operator variability in the

fabrication of thinner tabs but could not have influenced the results between days 1 and 2 discussed above. In addition, the blue colour of the silicone holder relative to the shade tab has to be considered as no barium sulphate was present to reflect the incoming light. However, it appeared this had little effect as the colour measurements did not show a shift toward the blue area of colour space.

Table 12 Most Common IdentaColor II Selections for Custom All-Ceramic Samples

		Day 1									Day 2								
	Tab Designation	**B1**			**A3**			**D4**			**B1**			**A3**			**D4**		
		Tab 1	*Tab 2*	*Tab 3*	*Tab 1*	*Tab 2*	*Tab 3*	*Tab 1*	*Tab 2*	*Tab 3*	*Tab 1*	*Tab 2*	*Tab 3*	*Tab 1*	*Tab 2*	*Tab 3*	*Tab 1*	*Tab 2*	*Tab 3*
1 mm	**Most Frequent Shade**	B2.5	B2.5	B2.5	B3.5	B3.5	B3.5	B3	B3	B3	B2.5	B2.5	B2.5	B3.5	B3.5	B3.5	B3.5	B3.5	B3.5
	No.of Times Selected	30	29	28	30	30	30	30	29	30	28	30	29	30	30	30	30	30	30
2 mm	**Most Frequent Shade**	A1.5	A1.5	A1.5	A3.5	A3.5	A3.5	B3.5	B3.5	B3.5	A1.5	A1.5	A1.5	A3.5	A3.5	A3.5	B3.5	B3.5	B3.5
	No.of Times Selected	30	30	29	30	30	30	29	29	29	30	29	30	30	29	30	29	29	29
3 mm	**Most Frequent Shade**	A1.25	A1.25	A1.25	A3.5	A3.5	A3.5	B3	B3	B3	A1.25	A1.25	A1.25	A3.5	A3.5	A3.5	B3	B3	B3
	No.of Times Selected	30	30	30	30	30	30	30	30	30	30	30	30	30	29	30	30	30	30
4 mm	**Most Frequent Shade**	A1.25	A1.25	A1.25	A3.5	A3.5	A3.5	B3.5	B3.5	B3.5	A1.25	A1.25	A1.25	A3.5	A3.5	A3.5	B3.5	B3.5	B3.5
	No.of Times Selected	29	28	30	29	28	30	29	28	30	29	30	30	30	30	30	30	30	30
5 mm	**Most Frequent Shade**	A1.25	A1.25	A1.25	A3.5	A3.5	A3.5	B3.5	B3.5	B3.5	A1.25	A1.25	A1.25	A3.5	A3.5	A3.5	B3.5	B3.5	B3.5
	No.of Times Selected	29	29	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30

5.1.4 Consistency of Repeated Measurements in each Data Set (Expts. 1 to 3)

The data sets from Experiments 1 to 3 were analysed further: Tables 6, 7 and 9 recorded that the coefficient of variation was greater than 1% for at least one colour co-ordinate of all the tabs on each day. This indicated that the consistency of the data in experiments 1 to 3 required further assessment by calculating colour differences (∆e). The ∆e (Table 13) was the colour difference between each individual reading in a data set and the mean of that data set. This was distinguished from the ∆E calculated previously (colour difference between the mean of 2 data sets).

Table 13 Mean Colour Differences (∆e) (±SD) between the Mean Colour Values of each Data Set and Individual Readings

	Shade	*Variable*	*Tab Surface Type*	*∆e*	
				Mean	**SD**
Expt. 1 (Calibration)	**A3**	**Before each data set**	*UNALTERED TAB*	**0.36**	0.19
			GROUND TAB	**0.28**	0.17
		After each measurement	*UNALTERED TAB*	**0.33**	0.25
			GROUND TAB	**0.39**	0.21
Expt. 2 (Lighting)	**B1**	**Dental Surgery**	*UNALTERED TAB*	**0.44**	0.30
			GROUND TAB	**0.63**	0.38
		Dark Room	*UNALTERED TAB*	**0.50**	0.34
			GROUND TAB	**0.45**	0.25
	A3	**Dental Surgery**	*UNALTERED TAB*	**0.25**	0.12
			GROUND TAB	**0.33**	0.20
		Dark Room	*UNALTERED TAB*	**0.25**	0.12
			GROUND TAB	**0.22**	0.13
	D4	**Dental Surgery**	*UNALTERED TAB*	**0.27**	0.15
			GROUND TAB	**0.23**	0.14
		Dark Room	*UNALTERED TAB*	**0.52**	0.26
			GROUND TAB	**0.26**	0.12
Expt. 3A (Time)	**B1**	**Day 1**	*UNALTERED TAB*	**0.44**	0.30
			GROUND TAB	**0.63**	0.38
		Day 2	*UNALTERED TAB*	**0.47**	0.25
			GROUND TAB	**0.37**	0.22
	A3	**Day 1**	*UNALTERED TAB*	**0.25**	0.12
			GROUND TAB	**0.33**	0.20
		Day 2	*UNALTERED TAB*	**0.20**	0.07
			GROUND TAB	**0.21**	0.09
	D4	**Day 1**	*UNALTERED TAB*	**0.27**	0.15
			GROUND TAB	**0.23**	0.14
		Day 2	*UNALTERED TAB*	**0.23**	0.16
			GROUND TAB	**0.28**	0.20

For both types of proprietary tab, no statistical differences between the colour differences (∆e) for calibration, lighting or time were found with the exception of the ground tabs in the calibration tests in experiment 1 ($p<0.05$): the colour differences were more consistent and lower when IdentaColor II requested re-calibration rather than re-calibrating after each measurement. This could have been due to positioning errors, despite the use of a parallelometer, as the probe had to be removed and replaced in latter series. It was concluded that the measurements of these tab surfaces were therefore repeatable.

Shade-dependent effects for ∆e were observed: B1 tabs had the largest mean values. The reasons for these findings might have been because (1) the scale used was not a recognised one and therefore application of the C.I.E.DE 2000 colour difference equation might not have been absolutely appropriate; however, it gave an indication of the direction of the colour change. The ∆e values would have been affected by IdentaColor II's scale being larger than C.I.E.'s. and (2) the environmental effects of temperature and humidity could theoretically have influenced the measurement of tabs but this seemed extremely unlikely. Interestingly, the unaltered D4 tabs in experiment 2 under dark room conditions, showed similar colour differences to the B1 tabs.

5.1.5 Colour Differences between Unaltered and Ground Proprietary Tabs (Expts. 1 to 3)

Table 14 recorded differences in α, β and γ values and the ∆E between the unaltered and ground tabs in experiments 1, 2 and 3A. These colour values were

significantly different with the exceptions of the α values ($p>0.05$) for shade A3 in experiment 1B (re-calibration after every measurement) and the B1 ($p>0.05$) and A3 ($p>0.05$) tabs under dental surgery lighting in experiment 2. Following grinding D4 tabs had the largest colour changes while A3 generally had the smallest. The tab surfaces of different shades may have been stained by different amounts therefore influencing the size of the change recorded. The α values of the ground tabs of B1 and D4 were lower (were darker) than those of the unaltered tabs. Generally, the A3 tabs followed this trend although some variation was seen across experiments 1 to 3. The β values remained constant or showed extremely small changes. The γ values of the ground tabs of shade B1 and D4 were consistently lower (less yellow) than the unaltered tabs. The A3 tabs showed the opposite changes, albeit not as large. These colour differences were probably due to (1) removal of the surface staining of the shade tab, (2) alteration of the surface texture, affecting the reflection of light, (3) alteration of the highly glazed shade tab surface, (4) differences in colour between the tabs of the same shade designation from two different shade guides, (5) spectrophotometer variation and (6) the colour scale used by IdentaColor II may have skewed the results.

Table 14 Differences in ΔE, using Mean Colour Values, between Proprietary Unaltered and Ground Shade Tabs

				Δα	Δβ	Δγ	ΔE
Expt. 1 (Calibration)	**Before each data set**	**A3**		-1.59	0.01	0.70	**1.18**
	After each measurement	**A3**		-0.25	0.01	0.39	**0.28**
Expt. 2 (Lighting)	**Dental Surgery**	**B1**		-0.49	0.01	-1.43	**0.78**
		A3		-0.02	0.01	0.56	**0.32**
		D4		-2.61	0.02	-2.38	**2.74**
	Dark Room	**B1**		-1.19	0.01	-2.73	**1.55**
		A3		-0.28	0.00	0.41	**0.30**
		D4		-2.48	0.09	-3.37	**3.15**
Expt. 3A (Time)	**Day 1**	**B1**		-0.49	0.01	-1.43	**0.78**
		A3		-0.02	0.01	0.56	**0.32**
		D4		-2.61	0.02	-2.38	**2.74**
	Day 2	**B1**		-1.74	0.01	-1.29	**1.17**
		A3		-0.02	0.01	0.52	**0.30**
		D4		-2.63	0.09	-2.38	**2.75**

5.1.6 Summary of the Conclusions concerning Expts. 1 to 3

It was unclear how IdentaColor II determined the shade from the colour values. The decision must have been based on the α, β and γ values and their balance, possibly with one component being more dominant than the others. The α, β and γ appeared to represent L*, a* and b* co-ordinates in some respects and therefore calculation of the Δe and ΔE values were deemed to have some validity and contributed to the discussion of IdentaColor II. The following conclusions concerning IdentaColor II's measurements were made:

- Colour values varied slightly with changes in the calibration method, lighting and time. It was therefore acceptable to measure samples under dental surgery lighting and re-calibrate when IdentaColor II requested.
- Unaltered tabs were measured with at least the same precision as ground ones.
- The colour measurements were reproducible within each data set.

- Small variations in the measurements of each tab, under the same conditions, on different days were found. These were unlikely to have a clinical significance.
- Colour values and shade selections were different following grinding of proprietary tabs: B1 and D4 tabs tended to have smaller α and γ values.
- The α scale was not linearly related to the 1976 C.I.E. L* scale. The α values showed a higher variation when α was large. This was reflected in larger values both in terms of ΔE and $\Delta\alpha$ differences.
- The β and γ values were again not absolutely equivalent to the C.I.E. scale and variation across these measurements were less than the α component.
- Experiments 2 and 3 demonstrated that the α and γ values decreased between shades B1, A3 and D4 whilst β increased, indicating that tabs decreased in lightness and increased in yellowness when progressing from B1 to A3 to D4.
- The thinner custom tabs of shades B1 and A3 were different shades from the thicker samples. However, D4 tabs remained approximately the same shade.
- The application of the acceptability/perceptibility thresholds was not valid when using IdentaColor II.
- IdentaColor II did not select the shade designation of the proprietary tabs or the all-ceramic tabs in any instance and its accuracy therefore has to be questioned.
- If the accuracy of measuring teeth could be verified then this could be an extremely useful clinical aid. It would allow the clinician and technician to objectively verify the shade of restorations under the different conditions found in the dental surgery and laboratory

If IdentaColor II's scale was representative if the C.I.E L*a*b* space then some colour differences between the different lighting conditions, re-calibration method and time would only just have been identifiable to trained observers under ideal lighting. However, it was determined that IdentaColor II used a scale with a larger range than this C.I.E. colour space. Therefore these colour differences were unlikely to have been visible. To confirm this, the data in Tables 9 and 11 were the colour values and shade selections of the proprietary tabs respectively were considered. It must be noted that the measurements had to be repeated as IdentaColor II cannot record both the shade and colour values at the same time. These data sets indicated the change in the colour values necessary to alter the shade selected. For example, changing from A1 to A2.5 meant that the α values decreased by around 20 units whilst the β values decreased by 6 units. When comparing A2.5 to A4, the same degree of movement on the Vita Classical scale, the α values also decreased by around 20 units whilst the β values decreased by 8 units. Changing the calibration method altered the colour values of unaltered tabs by a maximum of 0.73 α units and 0.57 β units (Table 6) whilst changing the lighting conditions changed the values by a maximum of 1 α unit and 0.7 β units (Table 8). It was concluded that the clinical effect of changing calibration method or lighting was negligible.

IdentaColor II recorded colour changes under different test conditions but could not provide quantitative data due to the lack of true L*a*b* dimensions. A spectrophotometer (Spectraflash SF600) was used to quantify the data changes in subsequent experiments. This enabled a better understanding of the colour changes after varying the mode of fabrication.

5.2 The Effects of Type and Thickness of Tab on Spectrophotometric Measurements using Spectraflash SF600 (Expt. 4)

Experiment 4 measured the colour co-ordinates of ceramic samples of three shades:

- Expt. 4A used proprietary shade tabs. These tabs were those used in the previous experiments
- Expt. 4B used custom all-ceramic tabs of different thicknesses. These tabs were those used in expt. 3 with the addition of custom-made all-ceramic 1.5 mm thickness tabs
- Expt. 4C used metal-ceramic tabs of varying, clinically relevant thicknesses (1, 1.5 and 2 mm)

A spectrophotometer (Spectraflash SF600) measured colour co-ordinates with accepted procedures. Re-calibration was only completed when the device sought it. ΔE_{00} values represented colour differences between the mean values of 2 data sets (similar to ΔE from IdentaColor II, except true L*, a* and b* co-ordinates were provided by the laboratory spectrophotometer).

5.2.1 The Spectrophotometric Measurement of Proprietary Shade Tabs (Expt. 4A)

Table 15 indicated that for the unaltered tabs, shade B1 was the lightest shade and D4 the darkest. D4 was considered to be the most chromatic (highest a* and b* values).

The summary of the results was recorded in Table 15, the 3D chart of the data displayed in Figure 5.4 and the colour differences (ΔE_{00}) between the different tab surface types (using day 1 results) and over time were recorded in Table 16. The bar charts for the unaltered and ground tabs of shade D4 were displayed in Figure 5.5.

The ground tabs were darker (lower L*) and less yellow (lower b*) whilst the a* exhibited the smallest changes (maximum = 0.38 units). Changes of up to 2.71 units L* units (D4) and 1.00 b* unit (A3) were found. The magnitude of the total colour difference (ΔE_{00}) varied with shade (B1=1.22, A3=1.76 and D4=2.48) but all would have been visible to human observers under ideal viewing conditions.

Table 15 Mean (±SD) Colour Co-ordinates (L*a*b*) + Coefficients of Variation % (CV) for Proprietary Shade Guide Tabs

			L*			a*			b*		
			Mean	**SD**	**CV**	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**
B1	**Experiment 4A (Day 1)**	UNALTERED TAB	71.71	0.00	0.01%	-0.63	0.00	-0.66%	8.23	0.01	0.07%
		GROUND TAB	70.17	0.00	0.00%	-0.41	0.00	-0.84%	8.16	0.01	0.08%
	Experiment 4A (Day 2)	UNALTERED TAB	71.22	0.00	0.00%	-0.62	0.00	-0.49%	8.13	0.00	0.06%
		GROUND TAB	70.03	0.00	0.00%	-0.46	0.00	-0.75%	7.89	0.01	0.07%
A3	**Experiment 4A (Day 1)**	UNALTERED TAB	68.30	0.01	0.01%	2.06	0.01	0.34%	14.54	0.01	0.04%
		GROUND TAB	66.29	0.00	0.01%	1.67	0.01	0.37%	13.55	0.01	0.05%
	Experiment 4A (Day 2)	UNALTERED TAB	68.12	0.00	0.01%	1.95	0.00	0.23%	14.42	0.00	0.03%
		GROUND TAB	66.50	0.01	0.01%	1.72	0.00	0.20%	14.13	0.01	0.04%
D4	**Experiment 4A (Day 1)**	UNALTERED TAB	59.60	0.00	0.00%	2.65	0.01	0.21%	14.68	0.01	0.06%
		GROUND TAB	56.89	0.00	0.01%	2.66	0.01	0.28%	13.97	0.01	0.06%
	Experiment 4A (Day 2)	UNALTERED TAB	59.60	0.00	0.01%	2.64	0.01	0.20%	14.69	0.01	0.04%
		GROUND TAB	57.21	0.00	0.01%	2.84	0.01	0.23%	13.71	0.00	0.04%

Figure 5.4. Mean L*a*b* Co-ordinates of Proprietary Shade Tabs

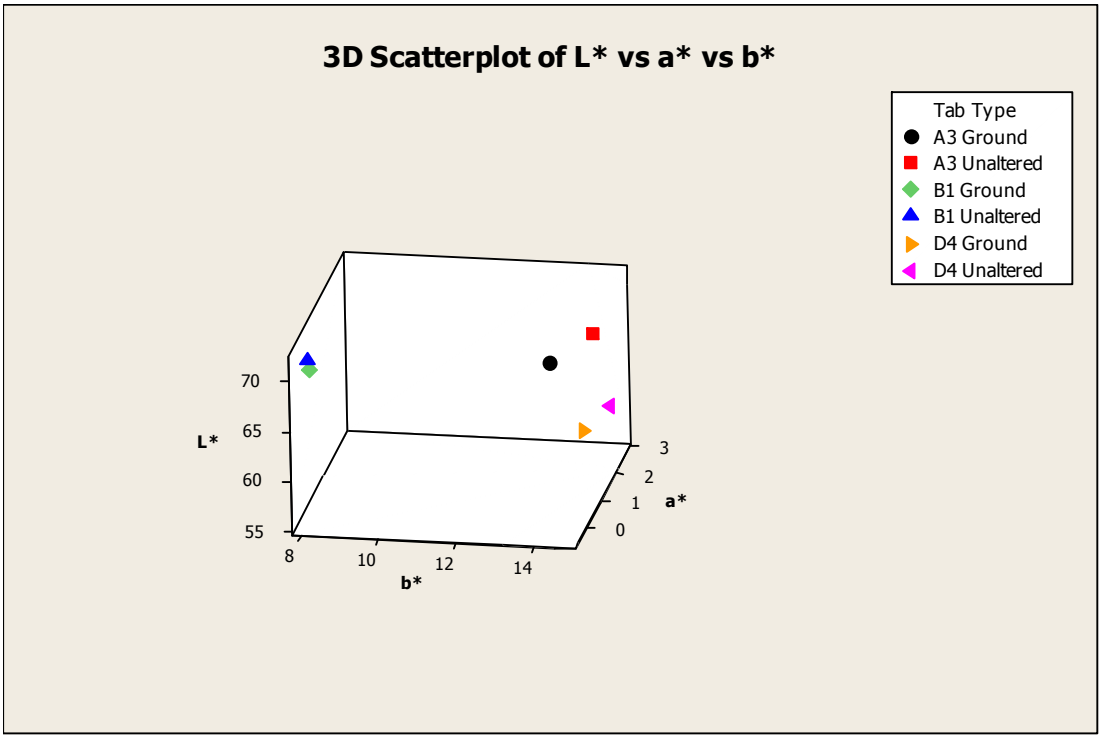
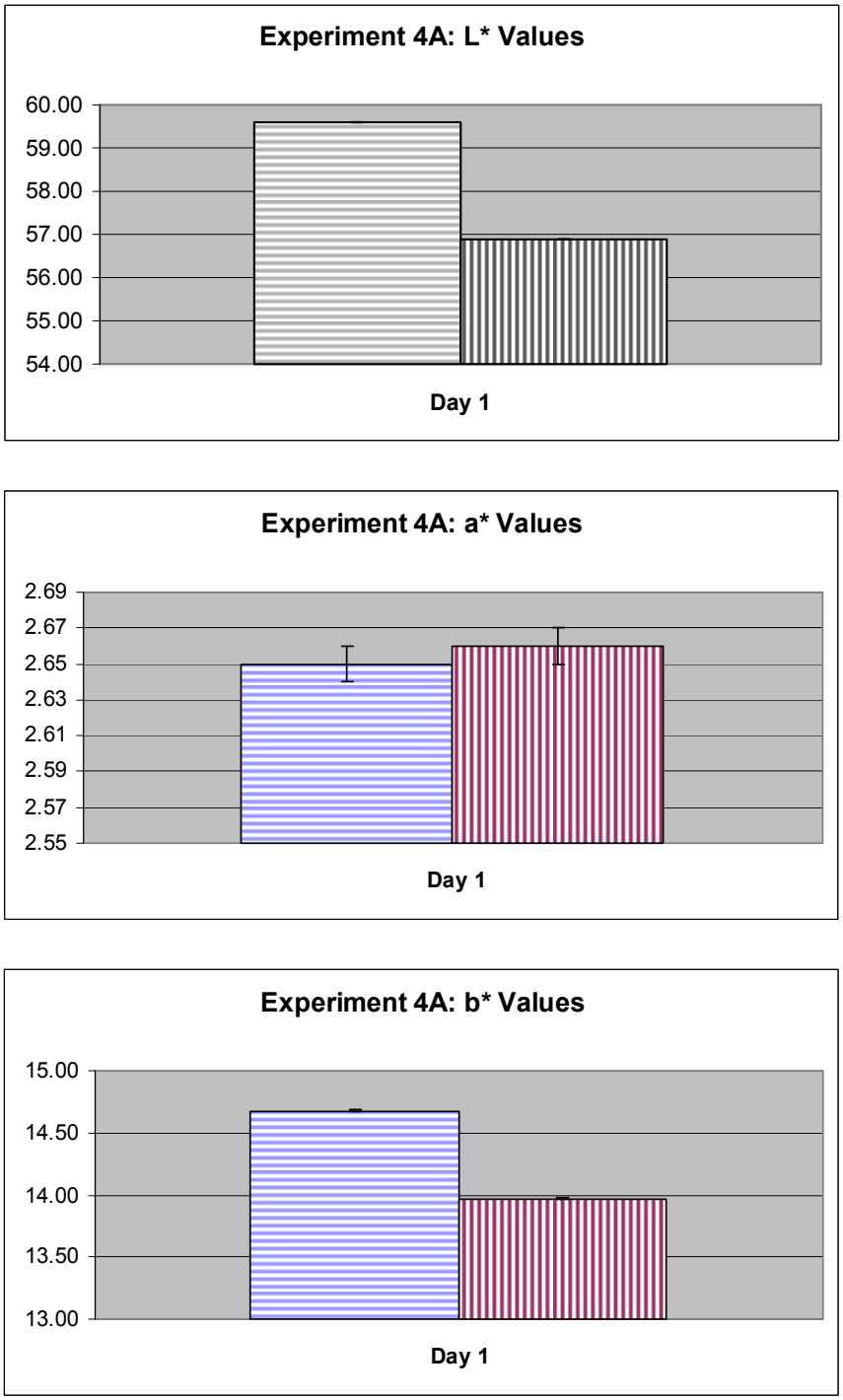


Table 16 Differences in ΔE_{00}, using Mean Colour Co-ordinates, between Days 1 and 2 and between Unaltered and Ground Proprietary Shade Tabs

		ΔL*	Δa*	Δb*	ΔE
ΔE Between Days 1 + 2 (Unaltered)					
	B1	-0.49	0.01	-0.10	**0.38**
	A3	-0.18	0.11	-0.12	**0.20**
	D4	0.00	-0.01	0.01	**0.01**
ΔE Between Days 1 + 2 (Ground)					
	B1	-0.14	-0.05	0.27	**0.24**
	A3	0.21	0.05	0.58	**0.40**
	D4	0.32	0.18	-0.26	**0.42**
ΔE Between Tab Surface Types					
	B1	-1.54	0.22	-0.06	**1.22**
	A3	-2.01	-0.38	-1.00	**1.76**
	D4	-2.71	0.02	-0.71	**2.48**

Figure 5.5. Mean (±SD) L*a*b* co-ordinates for Shade D4 Unaltered and Ground Proprietary Shade Tabs



The day 1 bar charts of α, β and γ values of shade D4 tabs were shown as they were representative of the samples. The scales used in the bar charts were not the same.

Table 17 recorded the colour co-ordinates of the porcelain shade guide tabs from experiments 3A (IdentaColor II) and 4A (Spectraflash SF600). The L*(α) co-ordinates were higher for all of the shades tested when IdentaColor II was used with less variation in the a*(β) values. The b*(γ) co-ordinates recorded by Spectraflash were higher for shade D4 but lower for the other shades. The largest changes were observed for shade B1 tabs, but no correlation between the scales was identified.

Table 17 IdentaColor II Colour Values and Spectraflash SF600 Colour Co-ordinates of Porcelain Shade Guide Tabs

SHADE	IDENTACOLOUR II				SPECTRAFLASH SF600		
	α	β	γ		L*	a*	b*
Unaltered Tabs							
B1	104.14	0.28	21.68		71.71	-0.63	8.23
A3	79.77	0.40	16.34		68.30	2.06	14.54
D4	65.45	0.52	10.67		59.60	2.65	14.68
Ground Tabs							
B1	103.65	0.29	20.25		70.17	-0.41	8.16
A3	79.75	0.41	16.90		66.29	1.67	13.55
D4	62.84	0.54	8.29		56.89	2.66	13.97

5.2.2 The Spectrophotometric Consistency of the Measurements (Expt. 4A)

The coefficient of variation was used to characterise consistency of measurement. This method gave similar information to the mean and standard deviations, however, the coefficient of variation allowed for comparison of data with substantially different means (L*, a* and b* colour co-ordinates). The coefficients of variation were substantially less for the data from the spectrophotometer compared to IdentaColor II throughout experiment 4. This indicated that Spectraflash had better short-term repeatability than IdentaColor II, although different colour scales were used. The small coefficients of variation in this experiment illustrated that the

smallest diameter aperture of the spectrophotometer was consistent in measuring both the custom ceramic samples and proprietary tabs.

The intra- and inter- data set consistency between the ground and unaltered tabs was very similar whilst the curved surfaces were measured with at least the same precision as the flat (ground) ones:

1. These results were highly consistent within each data set and over time. In experiment 4A (Table 15), the coefficient of variation did not exceed 1% with a maximum change of 0.04 units in any given data set.
2. The colour differences (ΔE_{00}) between the same tabs recorded on different days were small (Table 16). The maximum change was only just above the perceptibility threshold and was found for the ground D4 tab (0.42).

There were small colour differences between days 1 and 2, but the method of measurement was considered repeatable. The perceptibility threshold for this study was based on tests using textiles viewed under ideal conditions which do not represent the same conditions as dental ceramic and therefore these differences would not have been clinically perceptible.

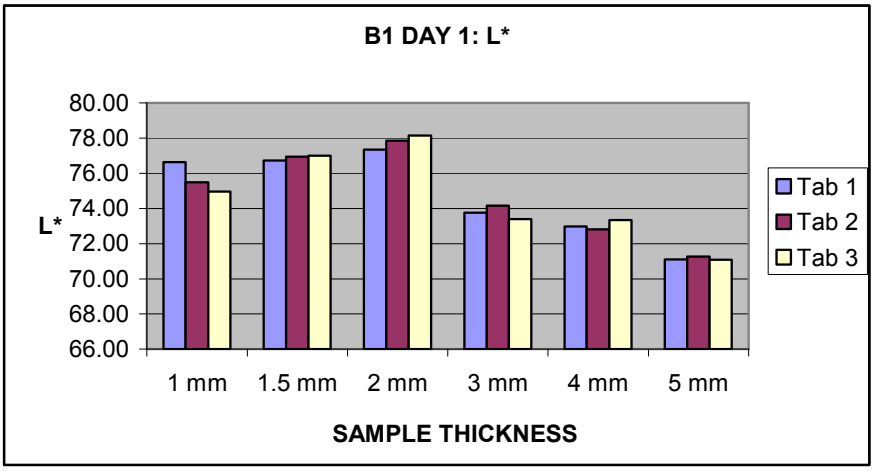
5.2.3 The Effect of Ceramic Thickness on the Spectrophotometric Measurement of All-Ceramic Tabs (Expt. 4B)

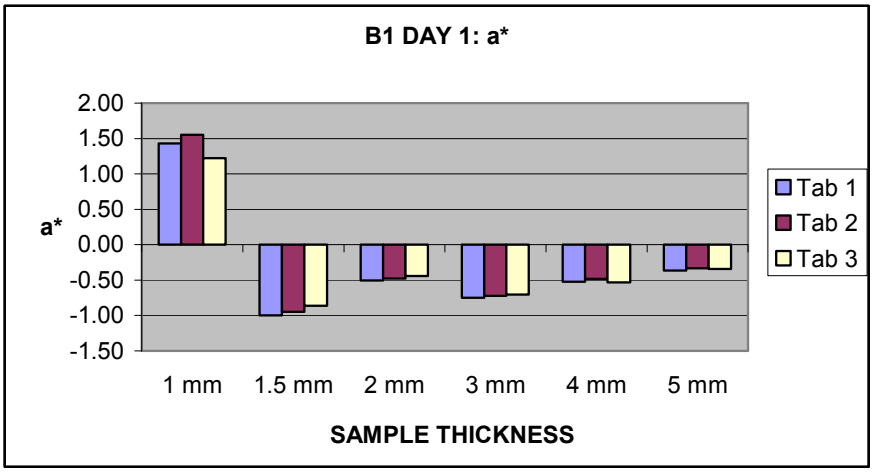
The summary of the results for each shade was recorded in Tables 18 to 20 and these results were shown both in 3D Charts and bar charts in Figures 5.6 to 5.11. The data from days 1 and 2 showed similar results and consequently only day 1 results were displayed.

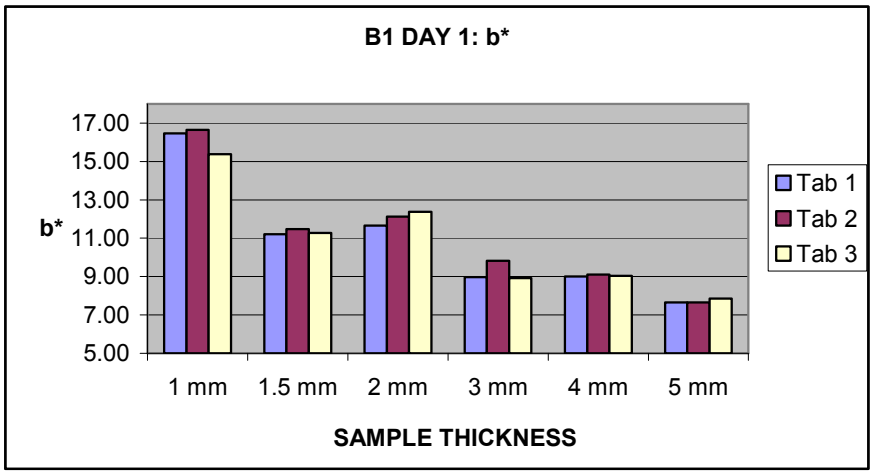
Table 18 Mean (±SD) Colour Co-ordinates (L*a*b*) + Coefficients of Variation % (CV) for Custom All-Ceramic Samples of Different Thicknesses (Shade B1)

			L*			a*			b*		
			Mean	**SD**	**CV**	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**
1 mm	*Day 1*	*Tab 1*	**76.63**	0.01	0.02%	**1.43**	0.01	0.35%	**16.47**	0.01	0.07%
		Tab 2	**75.48**	0.01	0.02%	**1.55**	0.00	0.28%	**16.65**	0.01	0.08%
		Tab 3	**74.96**	0.00	0.00%	**1.22**	0.01	0.51%	**15.36**	0.01	0.05%
	Day 2	*Tab 1*	**76.86**	0.00	0.00%	**1.49**	0.01	0.49%	**16.49**	0.01	0.04%
		Tab 2	**75.00**	0.00	0.00%	**1.54**	0.01	0.44%	**16.28**	0.01	0.04%
		Tab 3	**74.42**	0.00	0.00%	**1.43**	0.01	0.50%	**16.12**	0.01	0.04%
1.5 mm	*Day 1*	*Tab 1*	**76.74**	0.04	0.05%	**-1.00**	0.01	-0.85%	**11.21**	0.05	0.43%
		Tab 2	**76.95**	0.02	0.02%	**-0.95**	0.01	-1.01%	**11.46**	0.06	0.54%
		Tab 3	**76.99**	0.56	0.72%	**-0.86**	0.01	-1.34%	**11.27**	0.06	0.51%
	Day 2	*Tab 1*	**76.46**	0.01	0.02%	**-0.98**	0.01	-1.13%	**10.71**	0.02	0.14%
		Tab 2	**76.33**	0.02	0.02%	**-1.10**	0.01	-0.91%	**10.67**	0.01	0.12%
		Tab 3	**76.28**	0.01	0.02%	**-0.93**	0.01	-0.78%	**10.80**	0.01	0.14%
2 mm	*Day 1*	*Tab 1*	**77.36**	0.11	0.15%	**-0.51**	0.01	-1.00%	**11.65**	0.10	0.85%
		Tab 2	**77.86**	0.01	0.01%	**-0.47**	0.01	-1.53%	**12.12**	0.01	0.05%
		Tab 3	**78.14**	0.01	0.01%	**-0.44**	0.01	-1.19%	**12.37**	0.01	0.06%
	Day 2	*Tab 1*	**77.91**	0.01	0.01%	**-0.43**	0.01	-1.55%	**12.15**	0.01	0.07%
		Tab 2	**77.64**	0.01	0.01%	**-0.41**	0.01	-1.67%	**12.05**	0.01	0.05%
		Tab 3	**77.58**	0.01	0.01%	**-0.42**	0.01	-1.69%	**11.98**	0.01	0.05%
3 mm	*Day 1*	*Tab 1*	**73.76**	0.68	0.92%	**-0.75**	0.01	-0.95%	**8.97**	0.01	0.08%
		Tab 2	**74.16**	0.00	0.01%	**-0.72**	0.01	-0.87%	**9.81**	0.01	0.06%
		Tab 3	**73.39**	0.01	0.01%	**-0.71**	0.01	-0.97%	**8.92**	0.02	0.21%
	Day 2	*Tab 1*	**73.36**	0.01	0.01%	**-0.72**	0.01	-0.96%	**8.80**	0.01	0.06%
		Tab 2	**73.96**	0.01	0.01%	**-0.78**	0.01	-0.90%	**9.16**	0.01	0.07%
		Tab 3	**73.18**	0.00	0.01%	**-0.70**	0.01	-0.95%	**8.76**	0.01	0.08%
4 mm	*Day 1*	*Tab 1*	**72.97**	0.00	0.01%	**-0.52**	0.01	-1.13%	**9.00**	0.01	0.09%
		Tab 2	**72.80**	0.00	0.00%	**-0.48**	0.01	-1.46%	**9.11**	0.01	0.06%
		Tab 3	**73.35**	0.07	0.09%	**-0.54**	0.01	-0.95%	**9.02**	0.02	0.20%
	Day 2	*Tab 1*	**73.33**	0.01	0.01%	**-0.51**	0.01	-1.71%	**8.94**	0.01	0.08%
		Tab 2	**72.82**	0.01	0.01%	**-0.46**	0.01	-1.54%	**8.91**	0.01	0.06%
		Tab 3	**73.03**	0.01	0.01%	**-0.49**	0.01	-1.52%	**8.87**	0.01	0.07%
5 mm	*Day 1*	*Tab 1*	**71.09**	0.00	0.00%	**-0.36**	0.01	-1.56%	**7.64**	0.01	0.09%
		Tab 2	**71.26**	0.00	0.00%	**-0.33**	0.01	-1.61%	**7.64**	0.01	0.08%
		Tab 3	**71.08**	0.00	0.01%	**-0.34**	0.01	-2.19%	**7.85**	0.01	0.07%
	Day 2	*Tab 1*	**71.04**	0.01	0.01%	**-0.32**	0.01	-2.00%	**7.67**	0.01	0.07%
		Tab 2	**70.64**	0.00	0.01%	**-0.21**	0.01	-2.98%	**7.38**	0.01	0.10%
		Tab 3	**70.55**	0.00	0.00%	**-0.22**	0.01	-2.43%	**7.38**	0.01	0.08%

Figure 5.6. Mean L*a*b* Co-ordinates of Custom All-Ceramic Samples of Varying Thicknesses (Shade B1)







The scales used in the bar charts were not the same.

Figure 5.7. Mean L*a*b* Co-ordinates of Custom All-Ceramic Samples of Varying Thicknesses (Shade B1)

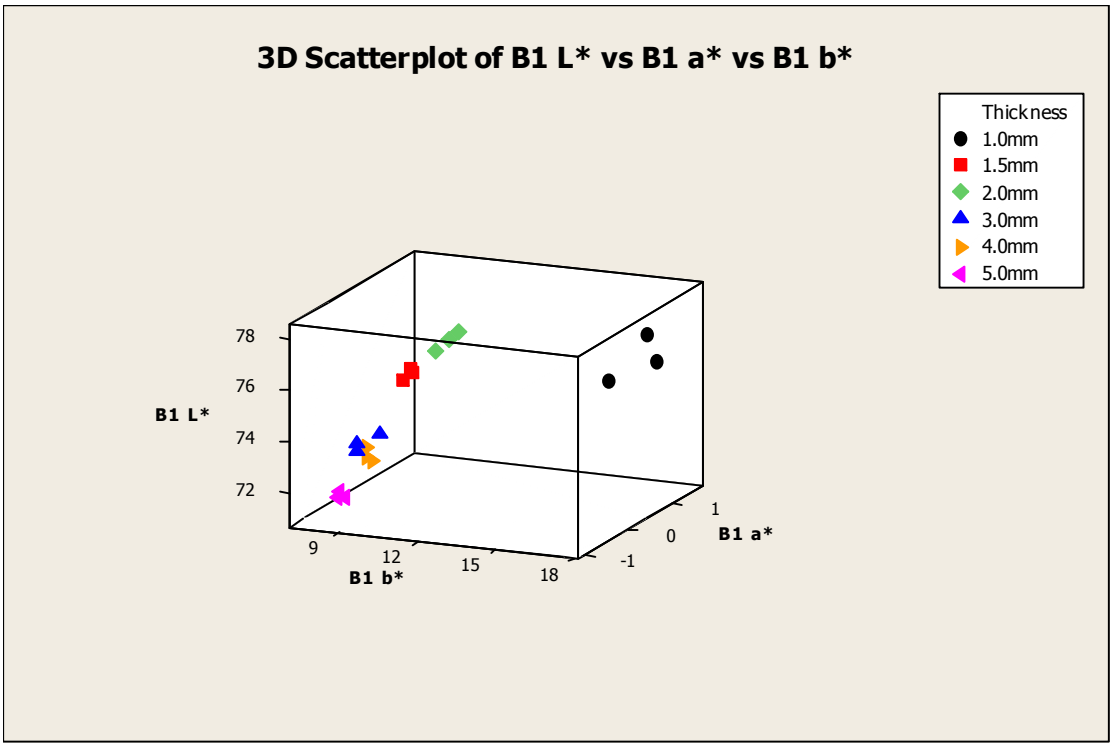
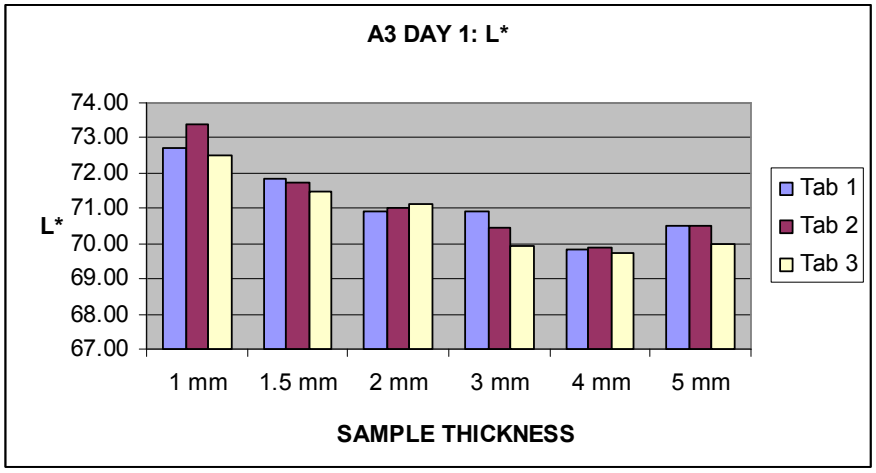
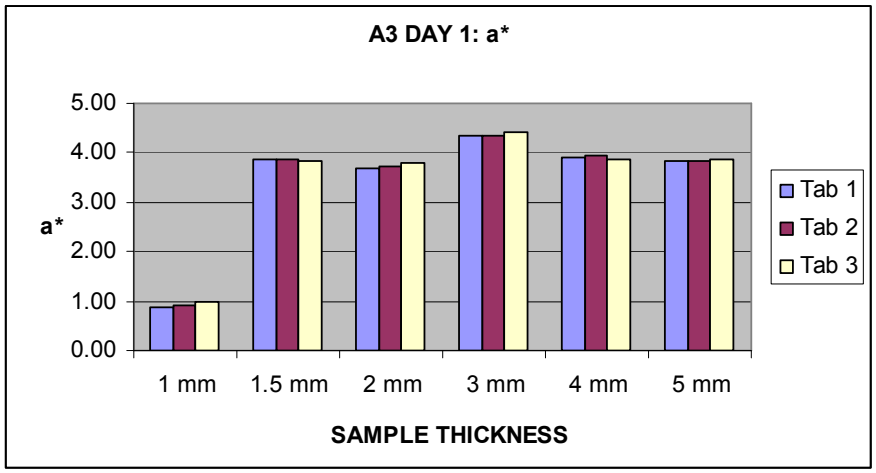


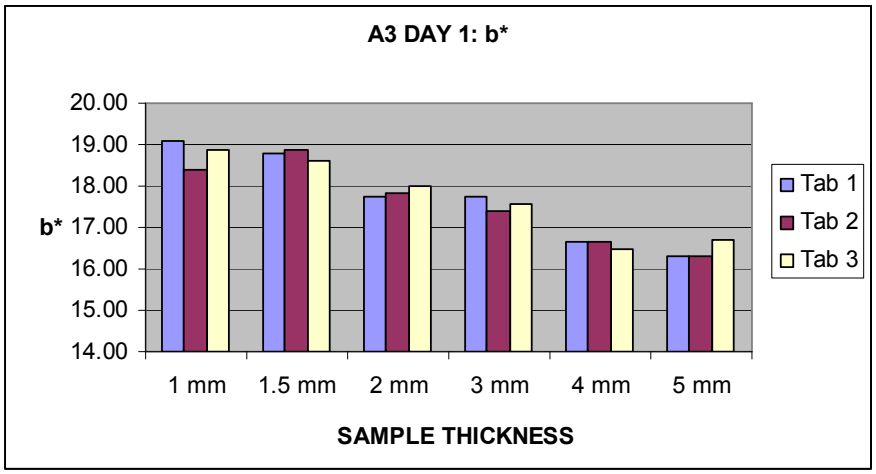
Table 19 Mean (±SD) Colour Co-ordinates (L*a*b*) + Coefficients of Variation % (CV) for Custom All-Ceramic Samples of Different Thicknesses (Shade A3)

			L*			a*			b*		
			Mean	**SD**	**CV**	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**
1 mm	*Day 1*	*Tab 1*	**72.72**	0.00	0.00%	**0.87**	0.01	0.77%	**19.08**	0.01	0.04%
		Tab 2	**73.36**	0.00	0.00%	**0.92**	0.01	0.85%	**18.37**	0.01	0.07%
		Tab 3	**72.48**	0.01	0.01%	**0.97**	0.01	0.88%	**18.86**	0.01	0.05%
	Day 2	*Tab 1*	**72.97**	0.00	0.01%	**1.08**	0.01	0.86%	**18.88**	0.01	0.06%
		Tab 2	**72.77**	0.00	0.01%	**0.99**	0.01	0.88%	**18.25**	0.01	0.05%
		Tab 3	**71.84**	0.00	0.01%	**0.96**	0.01	0.93%	**18.76**	0.01	0.05%
1.5 mm	*Day 1*	*Tab 1*	**71.86**	0.00	0.00%	**3.87**	0.01	0.18%	**18.77**	0.01	0.05%
		Tab 2	**71.72**	0.00	0.00%	**3.85**	0.01	0.18%	**18.85**	0.01	0.04%
		Tab 3	**71.49**	0.00	0.00%	**3.85**	0.00	0.08%	**18.61**	0.00	0.03%
	Day 2	*Tab 1*	**71.45**	0.00	0.00%	**3.79**	0.01	0.14%	**18.56**	0.01	0.05%
		Tab 2	**71.57**	0.00	0.01%	**3.78**	0.01	0.21%	**18.69**	0.01	0.03%
		Tab 3	**71.65**	0.00	0.01%	**3.82**	0.01	0.18%	**18.93**	0.01	0.03%
2 mm	*Day 1*	*Tab 1*	**70.91**	0.00	0.01%	**3.69**	0.00	0.13%	**17.75**	0.01	0.03%
		Tab 2	**71.00**	0.01	0.01%	**3.73**	0.01	0.14%	**17.85**	0.01	0.03%
		Tab 3	**71.13**	0.01	0.01%	**3.80**	0.01	0.15%	**17.99**	0.01	0.04%
	Day 2	*Tab 1*	**70.96**	0.01	0.01%	**3.85**	0.01	0.13%	**17.83**	0.01	0.04%
		Tab 2	**70.83**	0.01	0.01%	**3.81**	0.01	0.15%	**17.79**	0.01	0.05%
		Tab 3	**71.00**	0.01	0.01%	**3.83**	0.00	0.11%	**18.00**	0.01	0.04%
3 mm	*Day 1*	*Tab 1*	**70.93**	0.01	0.01%	**4.35**	0.00	0.10%	**17.73**	0.01	0.03%
		Tab 2	**70.45**	0.01	0.01%	**4.33**	0.00	0.10%	**17.41**	0.01	0.05%
		Tab 3	**69.93**	0.00	0.00%	**4.41**	0.00	0.06%	**17.56**	0.00	0.03%
	Day 2	*Tab 1*	**70.37**	0.01	0.01%	**4.37**	0.00	0.10%	**17.87**	0.01	0.05%
		Tab 2	**70.00**	0.01	0.01%	**4.27**	0.00	0.10%	**17.48**	0.01	0.03%
		Tab 3	**70.17**	0.01	0.01%	**4.23**	0.00	0.11%	**17.28**	0.01	0.04%
4 mm	*Day 1*	*Tab 1*	**69.84**	0.01	0.01%	**3.92**	0.01	0.14%	**16.66**	0.01	0.04%
		Tab 2	**69.88**	0.01	0.01%	**3.95**	0.01	0.13%	**16.67**	0.01	0.07%
		Tab 3	**69.71**	0.00	0.01%	**3.85**	0.00	0.12%	**16.46**	0.01	0.04%
	Day 2	*Tab 1*	**69.90**	0.00	0.01%	**3.90**	0.00	0.11%	**16.53**	0.01	0.05%
		Tab 2	**69.61**	0.00	0.01%	**3.91**	0.00	0.09%	**16.35**	0.01	0.04%
		Tab 3	**69.69**	0.01	0.01%	**3.98**	0.01	0.13%	**16.57**	0.01	0.05%
5 mm	*Day 1*	*Tab 1*	**70.49**	0.00	0.00%	**3.83**	0.00	0.07%	**16.30**	0.01	0.06%
		Tab 2	**70.52**	0.00	0.01%	**3.82**	0.00	0.13%	**16.31**	0.01	0.06%
		Tab 3	**70.00**	0.00	0.01%	**3.86**	0.00	0.10%	**16.68**	0.01	0.05%
	Day 2	*Tab 1*	**69.12**	0.00	0.01%	**3.76**	0.00	0.12%	**16.05**	0.01	0.04%
		Tab 2	**69.59**	0.01	0.01%	**3.82**	0.00	0.12%	**16.46**	0.01	0.06%
		Tab 3	**69.55**	0.01	0.01%	**4.01**	0.00	0.11%	**16.63**	0.01	0.05%

Figure 5.8. Mean L*a*b* Co-ordinates of Custom All-Ceramic Samples of Varying Thicknesses (Shade A3)







The scales used in the bar charts were not the same.

Figure 5.9. Mean L*a*b* Co-ordinates of Custom All-Ceramic Samples of Varying Thicknesses (Shade A3)

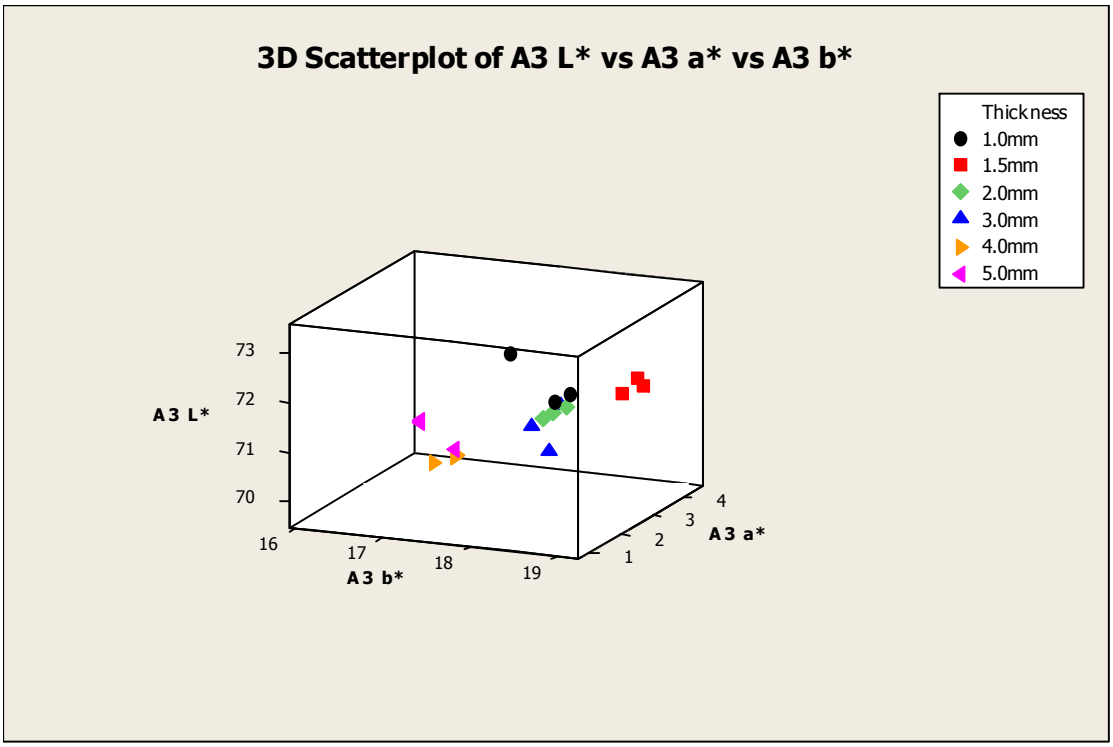
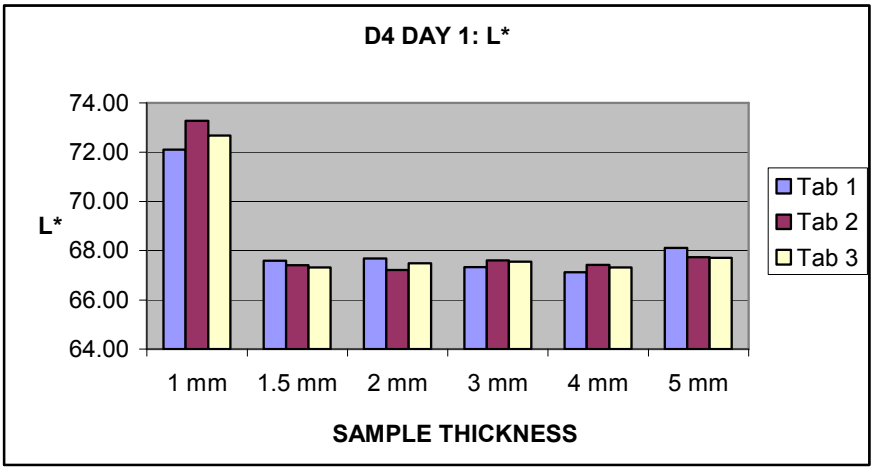
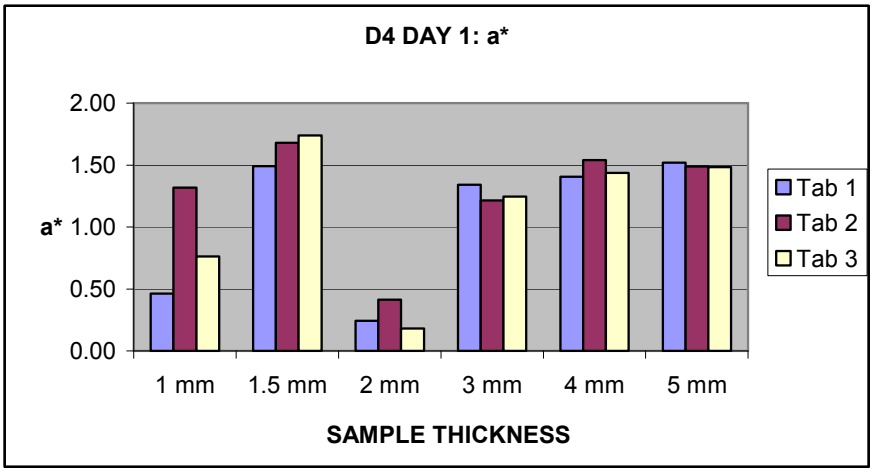


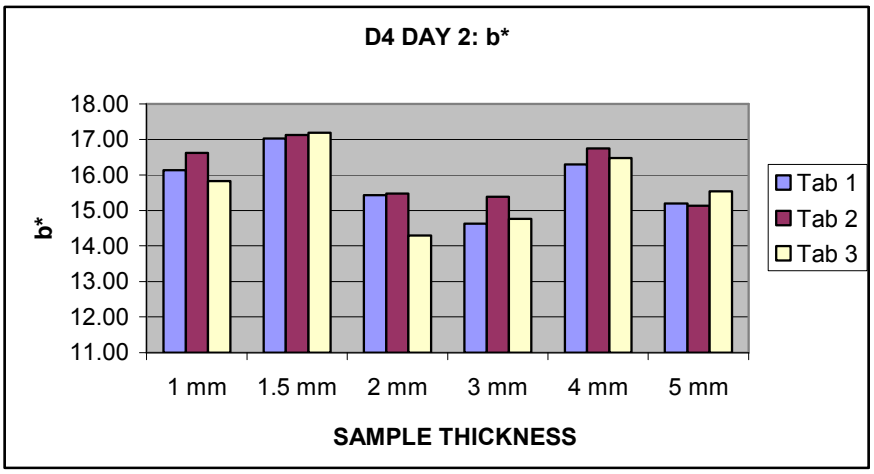
Table 20 Mean (±SD) Colour Co-ordinates (L*a*b*) + Coefficients of Variation % (CV) for Custom All-Ceramic Samples of Different Thicknesses (Shade D4)

			L*			a*			b*		
			Mean	**SD**	**CV**	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**
1 mm											
	Day 1	*Tab 1*	**72.10**	0.01	0.01%	**0.46**	0.01	1.56%	**15.06**	0.01	0.05%
		Tab 2	**73.27**	0.01	0.01%	**1.32**	0.01	0.74%	**17.73**	0.01	0.04%
		Tab 3	**72.67**	0.01	0.01%	**0.76**	0.01	1.08%	**15.74**	0.01	0.03%
	Day 2	*Tab 1*	**72.78**	0.01	0.01%	**0.94**	0.01	0.96%	**16.13**	0.01	0.03%
		Tab 2	**72.63**	0.01	0.01%	**1.03**	0.01	0.93%	**16.62**	0.01	0.04%
		Tab 3	**72.49**	0.01	0.01%	**0.80**	0.01	0.98%	**15.83**	0.01	0.04%
1.5 mm											
	Day 1	*Tab 1*	**67.59**	0.06	0.09%	**1.49**	0.02	1.29%	**17.02**	0.01	0.06%
		Tab 2	**67.40**	0.02	0.02%	**1.68**	0.02	1.04%	**17.08**	0.04	0.23%
		Tab 3	**67.32**	0.03	0.04%	**1.74**	0.02	1.02%	**17.01**	0.02	0.11%
	Day 2	*Tab 1*	**67.21**	0.01	0.01%	**1.79**	0.01	0.42%	**17.03**	0.03	0.15%
		Tab 2	**67.08**	0.02	0.03%	**1.87**	0.01	0.61%	**17.13**	0.03	0.17%
		Tab 3	**67.05**	0.02	0.03%	**1.78**	0.01	0.53%	**17.19**	0.02	0.09%
2 mm											
	Day 1	*Tab 1*	**67.68**	0.00	0.00%	**0.24**	0.01	3.09%	**14.68**	0.01	0.04%
		Tab 2	**67.21**	0.00	0.01%	**0.42**	0.01	1.97%	**15.64**	0.00	0.03%
		Tab 3	**67.49**	0.00	0.01%	**0.18**	0.01	6.42%	**14.79**	0.01	0.04%
	Day 2	*Tab 1*	**66.69**	0.01	0.01%	**0.39**	0.01	2.88%	**15.43**	0.01	0.04%
		Tab 2	**66.72**	0.00	0.01%	**0.40**	0.01	2.78%	**15.48**	0.01	0.04%
		Tab 3	**67.49**	0.01	0.01%	**0.31**	0.01	3.37%	**14.29**	0.01	0.04%
3 mm											
	Day 1	*Tab 1*	**67.33**	0.00	0.01%	**1.34**	0.01	0.53%	**14.88**	0.01	0.08%
		Tab 2	**67.60**	0.00	0.00%	**1.21**	0.01	0.63%	**14.47**	0.01	0.10%
		Tab 3	**67.55**	0.00	0.01%	**1.25**	0.01	0.62%	**14.41**	0.02	0.13%
	Day 2	*Tab 1*	**67.39**	0.01	0.01%	**1.33**	0.01	0.54%	**14.63**	0.02	0.11%
		Tab 2	**67.52**	0.00	0.01%	**1.53**	0.01	0.52%	**15.39**	0.01	0.08%
		Tab 3	**67.34**	0.00	0.01%	**1.32**	0.01	0.57%	**14.76**	0.01	0.09%
4 mm											
	Day 1	*Tab 1*	**67.13**	0.01	0.01%	**1.41**	0.01	0.48%	**16.38**	0.01	0.04%
		Tab 2	**67.43**	0.01	0.01%	**1.54**	0.01	0.53%	**16.17**	0.01	0.04%
		Tab 3	**67.32**	0.01	0.01%	**1.44**	0.01	0.59%	**16.23**		0.01
	Day 2	*Tab 1*	**67.08**	0.01	0.01%	**1.52**	0.01	0.46%	**16.29**	0.01	0.05%
		Tab 2	**66.84**	0.01	0.01%	**1.50**	0.01	0.59%	**16.74**	0.01	0.06%
		Tab 3	**66.58**	0.01	0.01%	**1.45**	0.01	0.60%	**16.48**	0.01	0.05%
5 mm											
	Day 1	*Tab 1*	**68.11**	0.00	0.00%	**1.52**	0.01	0.35%	**15.58**	0.01	0.08%
		Tab 2	**67.73**	0.00	0.00%	**1.49**	0.01	0.49%	**15.59**	0.01	0.08%
		Tab 3	**67.71**	0.00	0.01%	**1.48**	0.01	0.42%	**15.44**	0.01	0.08%
	Day 2	*Tab 1*	**67.72**	0.01	0.01%	**1.52**	0.01	0.52%	**15.20**	0.01	0.08%
		Tab 2	**67.91**	0.00	0.00%	**1.55**	0.01	0.45%	**15.14**	0.02	0.10%
		Tab 3	**67.42**	0.00	0.01%	**1.56**	0.01	0.61%	**15.54**	0.01	0.09%

Figure 5.10. Mean L*a*b* Co-ordinates of Custom All-Ceramic Samples of Varying Thicknesses (Shade D4)







The scales used in the bar charts were not the same.

Figure 5.11. Mean L*a*b* Co-ordinates of Custom All-Ceramic Samples of Varying Thicknesses (Shade D4)

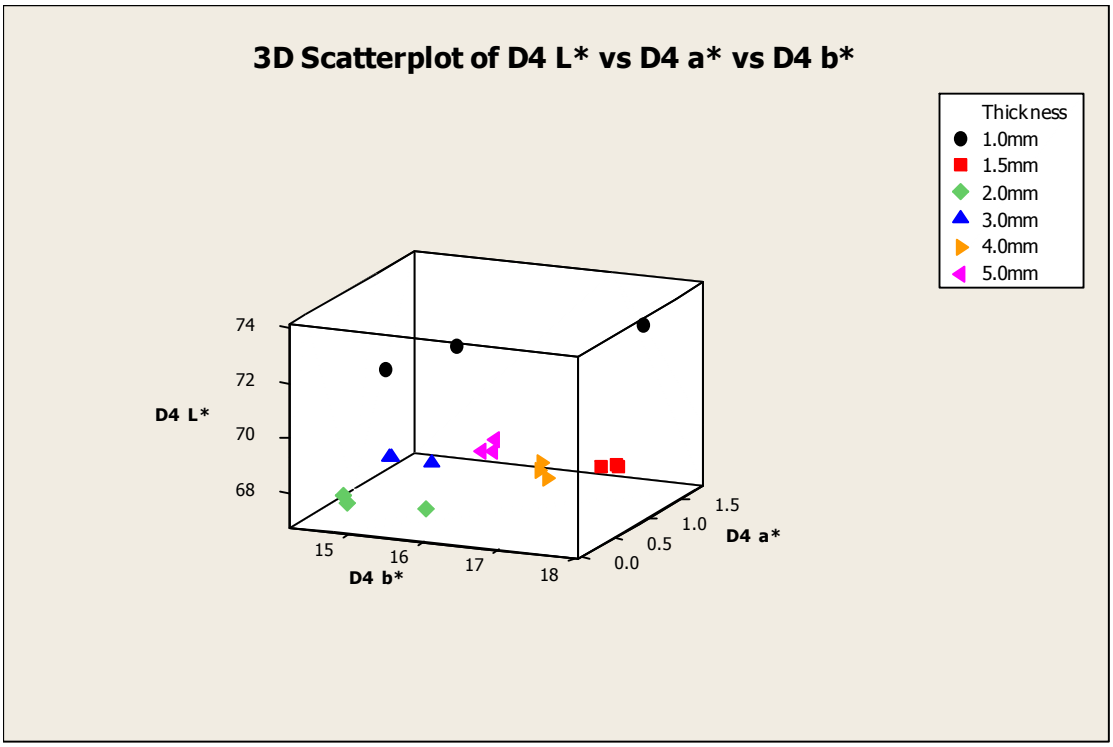


Table 21 recorded the colour differences (ΔE_{00}) between the colour co-ordinates of the porcelain shade guide tabs and the 2 and 4 mm custom-made all-ceramic tabs.

Table 21 Differences in ΔE_{00}, using Mean L*a*b* Co-ordinates, between Proprietary and Custom 2 & 4 mm All-Ceramic Tabs

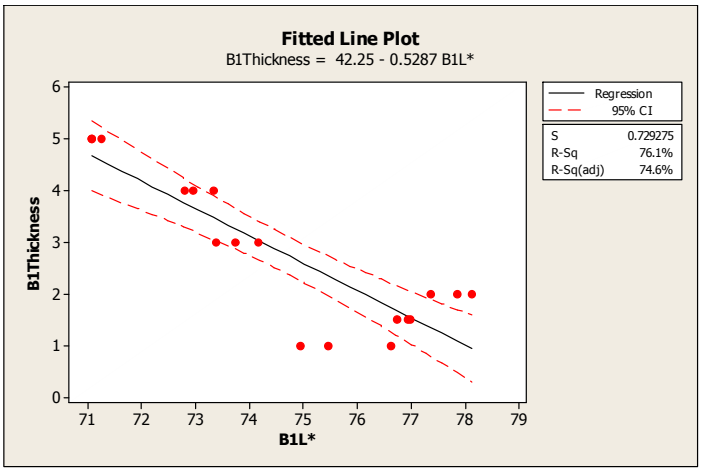
	ΔL*	Δa*	Δb*	ΔE_{00}
Unaltered v 2mm Tabs				
B1	6.08	0.16	3.82	**5.18**
A3	2.71	1.68	3.32	**3.28**
D4	7.86	-2.37	0.36	**7.23**
Unaltered v 4mm Tabs				
B1	1.33	0.10	0.81	**1.17**
A3	1.51	1.85	2.06	**2.60**
D4	7.69	-1.19	1.58	**6.71**

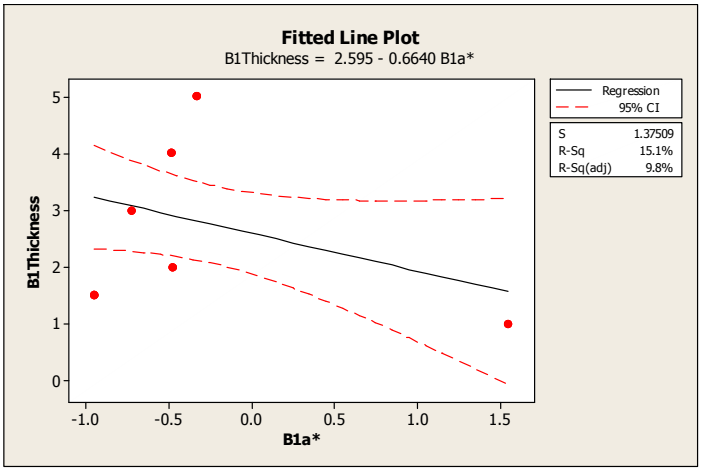
The data demonstrated several ceramic thickness and shade dependent trends but the colour differences (ΔE_{00}) in most instances were small. The linear regression analysis, with 95% confidence intervals, was shown in Figures 5.12 to 5.14 for shades B1, A3 and D4 respectively:

a. The tabs generally became darker (L* decreased) as the thickness of ceramic increased, especially once the thickness was >2 mm. Linear regression analysis found a relatively strong relationship between L* and ceramic thickness for shades B1 and A3 (R-sq = 76.1 and 68.0 respectively) but not for D4 (R-Sq=26.2). The 95% CI's were generally wider when the ceramic was thinner supporting the view that consistency of porcelain colour is more important in thinner sections. However, the L* values of the D4 tabs remained approximately constant above 1.5 mm, or decreased slightly. It was surmised that this shade, the darkest tested, reached its saturation point at a lower thickness than the other shades. All shades will have an end point, after which minimal L* changes would occur despite additional ceramic thickness. This appears to be reached at a lower thickness for shade D4.
b. With the exception of the 1 mm tabs of shades B1 and A3, the red-green values (a*) were near neutral whilst small variations were present regardless of the ceramic thickness. There was a weak correlation between a* and ceramic thickness. The A3 tabs showed the strongest correlation (R-Sq = 31.9), however the changes were very small. This trend was even less obvious for shades B1 (15.1) and D4 (6.1). These changes in colour could not be accounted for by any of the reasons postulated earlier.

c. The B1 and A3 tabs became less yellow (b* values decreased) as ceramic thickness increased (R-sq = 76.6 and 91.7 respectively). However, this trend was not evident for D4 (5.8).

Figure 5.12. Linear Regression of Mean L*a*b* Co-ordinates and Ceramic Thickness of Custom All-Ceramic Tabs (Shade B1)





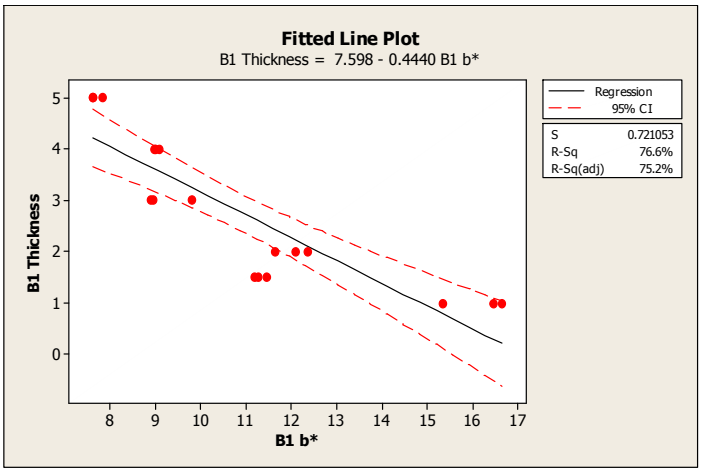
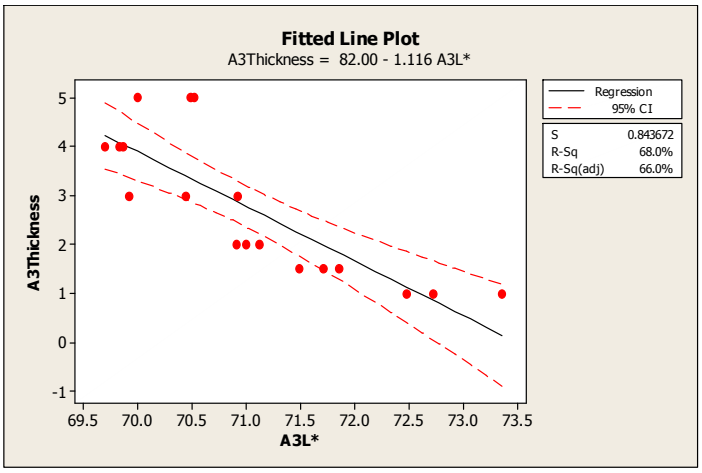
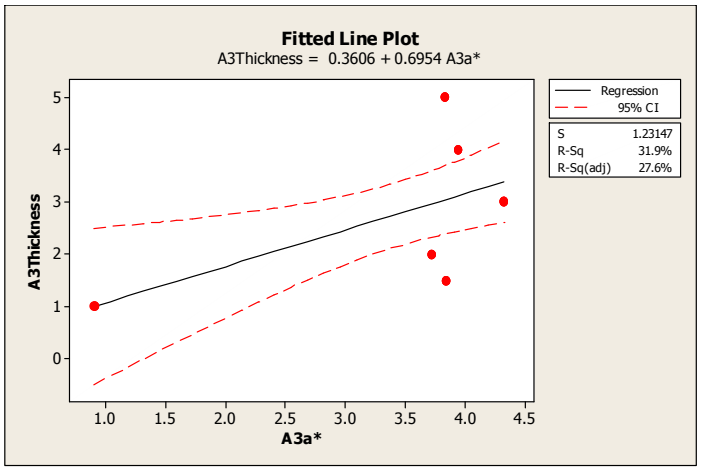


Figure 5.13. Linear Regression of Mean L*a*b* Co-ordinates and Ceramic Thickness of Custom All-Ceramic Tabs (Shade A3)





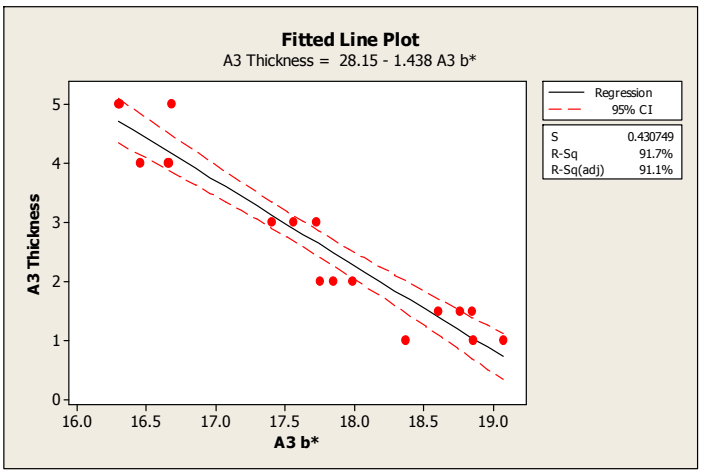
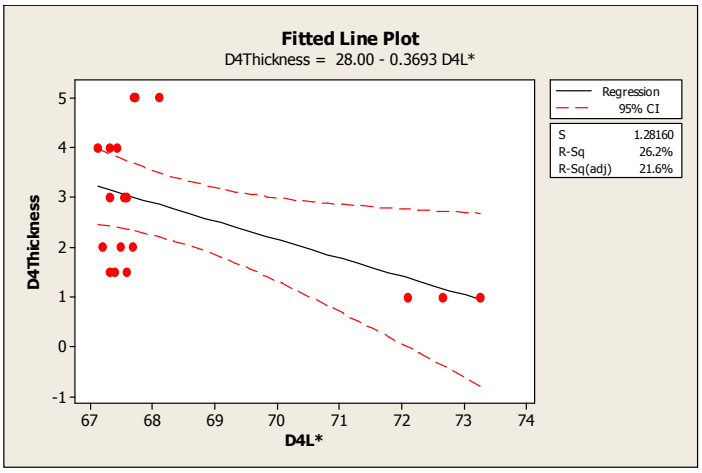
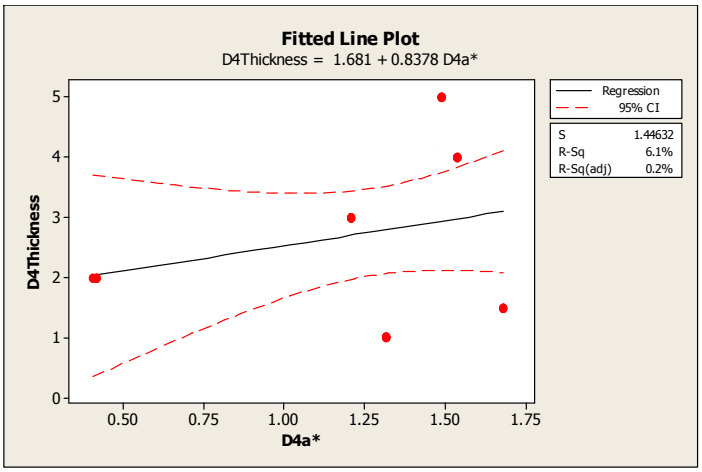
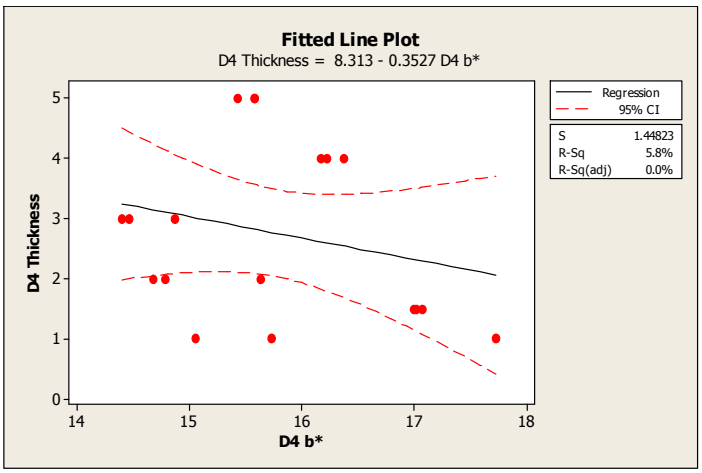


Figure 5.14. Linear Regression of Mean L*a*b* Co-ordinates and Ceramic Thickness of Custom All-Ceramic Tabs (Shade D4)







5.2.4 The Fabrication and Spectrophotometric Consistency of All-Ceramic Samples (Expt. 4B)

Consistency of Fabrication of Tabs from the Same Group

Table 22 recorded the colour differences (ΔE_{00}) between the 3 different tabs in each thickness and shade group. The thicker tabs and shade D4 tabs were less susceptible to colour co-ordinate variation within each group. The 1 mm tabs had more variability in their colour than the thicker tabs and had the largest mean differences; some within the same group would have been perceptible under ideal viewing conditions. These were likely to have been due to variations in sample preparation (fabrication) and presentation (edge-losses and background effects) which were more critical for thinner tabs.

Table 22 ΔE_{00}, using Mean L*a*b* Co-ordinates, between Custom Tabs of the Same Thickness of Three Different Shades

SHADE	Ceramic Thickness	Tabs Compared	ΔE_{00} Day 1	ΔE_{00} Day 2	Ceramic Thickness	Tabs Compared	ΔE_{00} Day 1	ΔE_{00} Day 2
B1	**1 millimetre**	1 to 2	0.85	1.35	**3 millimetres**	1 to 2	0.61	0.52
		1 to 3	1.38	1.78		1 to 3	0.29	0.14
		2 to 3	0.9	0.45		2 to 3	0.85	0.65
	1.5 millimetres	1 to 2	0.39	0.19	**4 millimetres**	1 to 2	0.16	0.38
		1 to 3	0.26	0.16		1 to 3	0.29	0.23
		2 to 3	0.23	0.25		2 to 3	0.42	0.16
	2 millimetres	1 to 2	0.47	0.21	**5 millimetres**	1 to 2	0.14	0.4
		1 to 3	0.73	0.26		1 to 3	0.16	0.45
		2 to 3	0.26	0.06		2 to 3	0.21	0.07
A3	**1 millimetre**	1 to 2	0.62	0.38	**3 millimetres**	1 to 2	0.41	0.37
		1 to 3	0.24	0.86		1 to 3	0.78	0.37
		2 to 3	0.71	0.76		2 to 3	0.42	0.17
	1.5 millimetres	1 to 2	0.12	0.13	**4 millimetres**	1 to 2	0.05	0.26
		1 to 3	0.29	0.25		1 to 3	0.16	0.19
		2 to 3	0.22	0.14		2 to 3	0.2	0.15
	2 millimetres	1 to 2	0.09	0.11	**5 millimetres**	1 to 2	0.03	0.43
		1 to 3	0.23	0.11		1 to 3	0.44	0.52
		2 to 3	0.14	0.18		2 to 3	0.46	0.22
D4	**1 millimetre**	1 to 2	2.00	0.32	**3 millimetres**	1 to 2	0.35	0.51
		1 to 3	0.68	0.32		1 to 3	0.35	0.09
		2 to 3	1.36	0.54		2 to 3	0.07	0.45
	1.5 millimetres	1 to 2	0.27	0.15	**4 millimetres**	1 to 2	0.32	0.32
		1 to 3	0.37	0.16		1 to 3	0.18	0.43
		2 to 3	0.11	0.12		2 to 3	0.16	0.27
	2 millimetres	1 to 2	0.71	0.04	**5 millimetres**	1 to 2	0.3	0.16
		1 to 3	0.18	0.94		1 to 3	0.33	0.32
		2 to 3	0.62	0.94		2 to 3	0.09	0.46

Analyses confirmed these to be statistically significant thickness-dependent differences for shade B1 ($p<0.02$). The A3 tabs showed similar statistical findings with regard to thickness. However, the 3 and 5 mm A3 tabs also had larger mean colour differences than the other thicknesses, therefore no statistical differences between tabs of 1 and 3 ($p>0.05$) and 1 and 5 ($p>0.05$) mm were found. For D4, statistical differences were found between the 1 and 1.5 ($p<0.05$) and 1.5 and 2 ($p<0.05$) mm tabs.

The colour co-ordinates in the data sets of the D4 tabs were more consistent than those from the other shades ($p<0.05$). These findings may be due to D4's ability to reduce measurement errors (edge-losses and background influences) in a similar fashion to the thicker tabs discussed earlier. In addition, variability in operator's fabrication was possibly more critical for the lighter shades (B1 & A3).

Consistency of Spectrophotometric Measurements

Table 23 recorded the colour differences (ΔE_{00}) between days 1 and 2 for each tab. The intra-data set consistency was excellent. Tables 18 and 20 demonstrated that several a* values had coefficients of variation of greater than 1 % in expt. 4B, but the actual changes were very small (0.06 units):

i. B1 (Table 18): 1.5, 2, 4 and 5 mm (Day 1) and 1.5, 2, 4 and 5 mm (Day 2)
ii. D4 (Table 20): 1 and 2 mm (Day 1) and 1.5 and 2 mm (Day 2)

Table 23 Differences in ΔE_{00}, using Mean L*a*b* Co-ordinates, between Days 1 and 2 for Custom All-Ceramic Tabs

	Thickness		1mm		1.5mm		2mm		3mm		4mm		5 mm
	Tab												
B1	1		0.18		0.39		0.52		0.35		0.27		0.08
	2		0.41		0.73		0.18		0.49		0.14		0.53
	3		0.63		0.61		0.47		0.2		0.27		0.56
A3	1		0.32		0.34		0.18		0.44		0.09		1.07
	2		0.45		0.25		0.17		0.36		0.28		0.73
	3		0.49		0.23		0.1		0.29		0.15		0.39
D4	1		0.98		0.47		0.93		0.16		0.16		0.38
	2		0.84		0.34		0.41		0.65		0.58		0.32
	3		0.15		0.24		0.35		0.28		0.61		0.25

The mean colour difference (ΔE_{00}) between days 1 and 2 (Table 23) was 0.39 (±0.23) which was below the perceptibility threshold. The differences in colour co-ordinates can be explained by: (1) the device's inherent day-to-day variation and (2) the amount of light lost due to edge-loss errors might have varied slightly in the experiments, giving a small change in the co-ordinates. Although the day-to-day variation would have predominated. Positioning errors were unlikely to have contributed, as the same point was measured on each sample and verified by means of the holder's orientation.

5.2.5 The Effects of Ceramic Thickness on Spectrophotometric Measurements of Metal-Ceramic Tabs (Expt. 4C)

The summary of the results was recorded in Tables 24, 25 and 26 and in 3D Charts (Figures 5.15 to 5.17) for shades B1, A3 and D4.

Table 27 recorded the colour differences (ΔE_{00}) between the different tab types (proprietary, custom all-ceramic and custom metal-ceramic).

Table 24 Mean (±SD) Colour Co-ordinates (L*a*b*) + Coefficients of Variation % (CV) for Custom Metal-Ceramic Samples of Different Thicknesses (Shade B1)

			L*			a*			b*		
			Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
1 mm	Day 1	*Tab 1*	**72.53**	0.00	0.01%	**0.95**	0.01	0.65%	**11.74**	0.01	0.09%
		Tab 2	**73.72**	0.00	0.00%	**0.42**	0.01	1.38%	**11.12**	0.01	0.08%
		Tab 3	**73.83**	0.19	0.26%	**1.14**	0.02	1.55%	**11.22**	0.07	0.59%
	Day 2	*Tab 1*	**72.82**	0.00	0.01%	**0.98**	0.01	0.69%	**11.62**	0.01	0.11%
		Tab 2	**73.40**	0.00	0.01%	**0.44**	0.01	1.26%	**11.32**	0.01	0.09%
		Tab 3	**74.23**	0.01	0.01%	**1.18**	0.01	0.48%	**11.39**	0.02	0.16%
1.5 mm	Day 1	*Tab 1*	**73.45**	0.00	0.00%	**0.17**	0.01	4.14%	**11.81**	0.01	0.07%
		Tab 2	**73.69**	0.00	0.01%	**0.17**	0.01	3.78%	**12.10**	0.01	0.09%
		Tab 3	**73.52**	0.01	0.01%	**0.14**	0.01	4.40%	**12.07**	0.01	0.08%
	Day 2	*Tab 1*	**73.67**	0.00	0.00%	**0.18**	0.01	3.08%	**11.72**	0.01	0.08%
		Tab 2	**73.86**	0.01	0.01%	**0.15**	0.01	4.37%	**11.74**	0.01	0.07%
		Tab 3	**73.42**	0.01	0.01%	**0.05**	0.01	12.97%	**12.16**	0.01	0.05%
2 mm	Day 1	*Tab 1*	**72.86**	0.01	0.01%	**0.04**	0.01	21.02%	**9.76**	0.01	0.10%
		Tab 2	**72.88**	0.01	0.01%	**-0.33**	0.01	-1.57%	**9.07**	0.01	0.12%
		Tab 3	**71.89**	0.01	0.01%	**-0.46**	0.01	-1.27%	**9.26**	0.01	0.08%
	Day 2	*Tab 1*	**72.07**	0.01	0.01%	**0.02**	0.01	42.28%	**9.89**	0.01	0.09%
		Tab 2	**72.15**	0.01	0.01%	**-0.24**	0.01	-3.19%	**9.55**	0.01	0.09%
		Tab 3	**71.80**	0.00	0.01%	**-0.49**	0.01	-1.30%	**9.02**	0.01	0.09%

Figure 5.15. Mean L*a*b* Co-ordinates of Custom Metal-Ceramic Samples of Varying Thicknesses (Shade B1, Day 1)

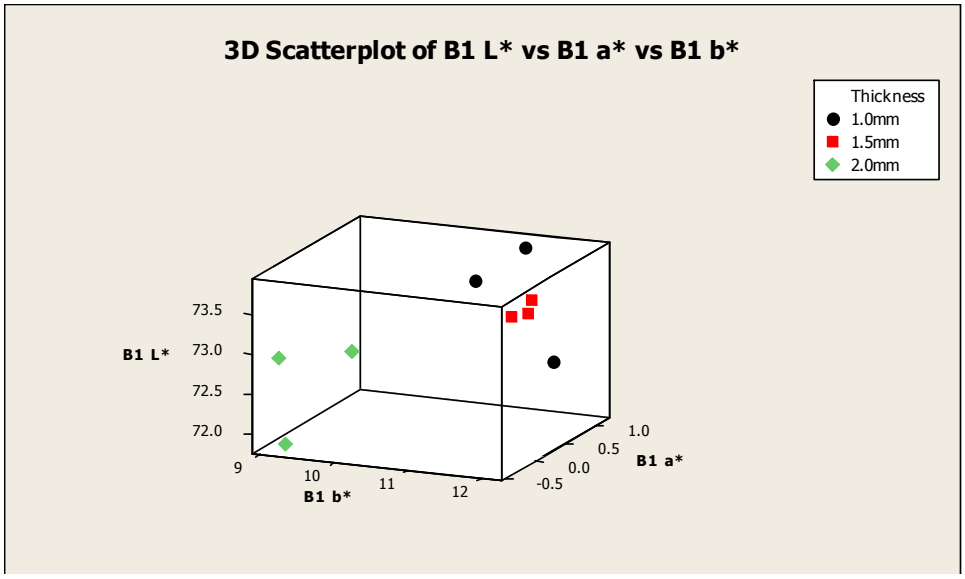


Table 25 Mean (±SD) Colour Co-ordinates (L*a*b*) + Coefficients of Variation % (CV) for Custom Metal-Ceramic Samples of Different Thicknesses (Shade A3)

			L*			a*			b*		
			Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
1 mm	Day 1	Tab 1	**75.72**	0.01	0.01%	**5.01**	0.01	0.13%	**17.84**	0.01	0.07%
		Tab 2	**75.50**	0.00	0.00%	**4.70**	0.01	0.14%	**17.93**	0.01	0.05%
		Tab 3	**75.33**	0.00	0.00%	**5.02**	0.01	0.14%	**17.38**	0.01	0.07%
	Day 2	Tab 1	**75.96**	0.00	0.01%	**4.92**	0.01	0.13%	**17.59**	0.01	0.07%
		Tab 2	**74.74**	0.00	0.00%	**4.62**	0.01	0.13%	**17.68**	0.01	0.05%
		Tab 3	**75.83**	0.00	0.00%	**4.89**	0.01	0.12%	**17.58**	0.01	0.05%
1.5 mm	Day 1	Tab 1	**75.46**	0.00	0.00%	**4.57**	0.01	0.14%	**17.54**	0.01	0.04%
		Tab 2	**75.15**	0.00	0.01%	**4.66**	0.01	0.13%	**17.52**	0.01	0.05%
		Tab 3	**75.30**	0.00	0.00%	**4.56**	0.01	0.15%	**17.92**	0.01	0.05%
	Day 2	Tab 1	**75.14**	0.00	0.00%	**4.46**	0.01	0.14%	**17.88**	0.01	0.06%
		Tab 2	**76.08**	0.00	0.00%	**4.92**	0.01	0.11%	**17.46**	0.01	0.06%
		Tab 3	**75.12**	0.00	0.01%	**4.60**	0.01	0.15%	**17.95**	0.01	0.05%
2 mm	Day 1	Tab 1	**69.11**	0.00	0.00%	**3.86**	0.01	0.15%	**15.89**	0.01	0.07%
		Tab 2	**69.26**	0.00	0.00%	**3.91**	0.01	0.14%	**15.76**	0.01	0.07%
		Tab 3	**69.37**	0.00	0.00%	**4.05**	0.01	0.15%	**16.17**	0.02	0.10%
	Day 2	Tab 1	**69.60**	0.00	0.00%	**4.07**	0.00	0.12%	**15.66**	0.01	0.06%
		Tab 2	**69.55**	0.00	0.00%	**4.04**	0.01	0.15%	**15.90**	0.01	0.06%
		Tab 3	**69.40**	0.00	0.01%	**3.96**	0.01	0.18%	**15.67**	0.02	0.11%

Figure 5.16. Mean L*a*b* Co-ordinates of Custom Metal-Ceramic Samples of Varying Thicknesses (Shade A3, Day 1)

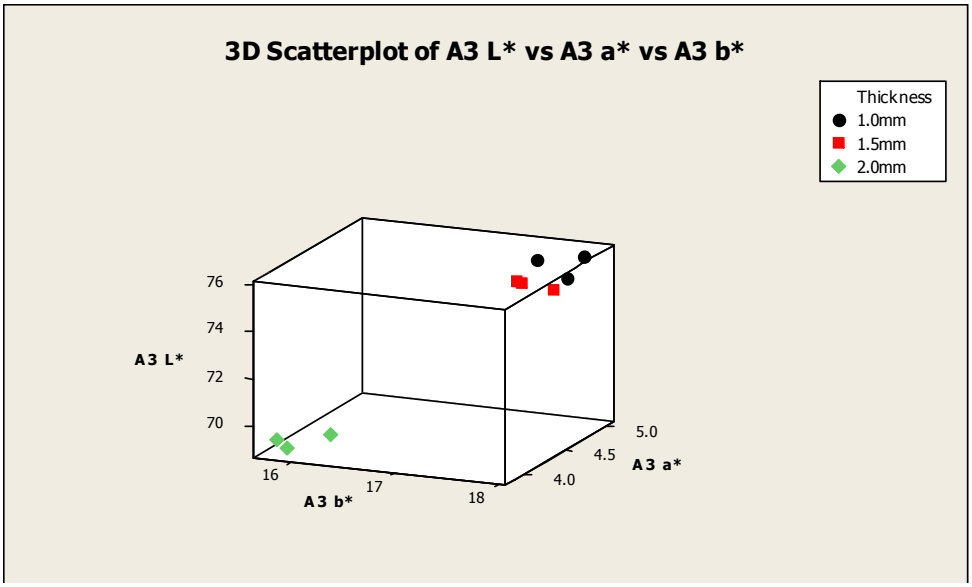


Table 26 Mean (±SD) Colour Co-ordinates (L*a*b*) + Coefficients of Variation % (CV) for Custom Metal-Ceramic Samples of Different Thicknesses (Shade D4)

			L*			a*			b*		
			Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
1 mm	Day 1	Tab 1	**71.56**	0.00	0.00%	**3.59**	0.01	0.16%	**18.25**	0.01	0.07%
		Tab 2	**71.07**	0.00	0.00%	**3.53**	0.01	0.16%	**18.86**	0.01	0.06%
		Tab 3	**71.44**	0.00	0.00%	**3.51**	0.01	0.18%	**18.52**	0.02	0.11%
	Day 2	Tab 1	**71.54**	0.00	0.00%	**3.53**	0.00	0.13%	**18.62**	0.01	0.05%
		Tab 2	**71.44**	0.00	0.00%	**3.56**	0.01	0.21%	**18.43**	0.01	0.04%
		Tab 3	**71.15**	0.00	0.01%	**3.60**	0.01	0.16%	**18.68**	0.01	0.07%
1.5 mm	Day 1	Tab 1	**69.82**	0.00	0.00%	**2.85**	0.01	0.21%	**19.37**	0.01	0.06%
		Tab 2	**69.58**	0.01	0.01%	**2.62**	0.01	0.24%	**19.34**	0.01	0.05%
		Tab 3	**69.93**	0.00	0.00%	**3.22**	0.01	0.23%	**20.02**	0.01	0.05%
	Day 2	Tab 1	**69.65**	0.00	0.01%	**2.84**	0.01	0.33%	**19.08**	0.01	0.06%
		Tab 2	**69.48**	0.00	0.01%	**2.65**	0.00	0.18%	**20.09**	0.01	0.06%
		Tab 3	**69.83**	0.00	0.00%	**3.01**	0.01	0.21%	**19.30**	0.01	0.05%
2 mm	Day 1	Tab 1	**68.44**	0.00	0.01%	**2.37**	0.01	0.24%	**17.43**	0.01	0.07%
		Tab 2	**68.05**	0.01	0.01%	**2.19**	0.01	0.33%	**17.53**	0.03	0.15%
		Tab 3	**68.60**	0.00	0.01%	**2.19**	0.01	0.31%	**17.30**	0.01	0.06%
	Day 2	Tab 1	**68.44**	0.00	0.00%	**2.37**	0.01	0.24%	**17.17**	0.01	0.05%
		Tab 2	**67.98**	0.01	0.43%	**2.23**	0.01	0.03%	**17.22**	0.03	0.17%
		Tab 3	**68.32**	0.00	0.00%	**2.24**	0.01	0.32%	**16.94**	0.01	0.08%

Figure 5.17. Mean L*a*b* Co-ordinates of Custom Metal-Ceramic Samples of Varying Thicknesses (Shade D4, Day 1)

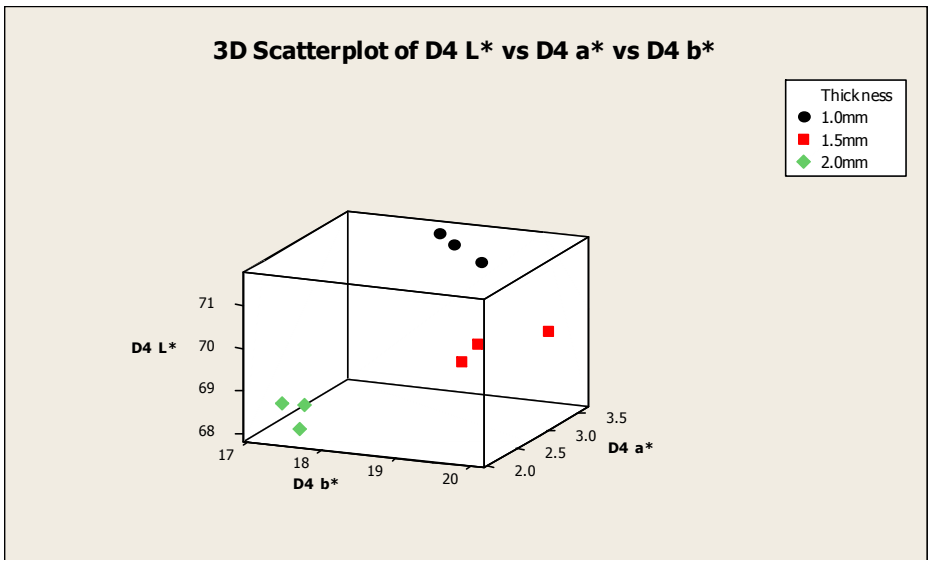


Table 27 Differences in ΔE_{00}, using Mean L*a*b* Co-ordinates, between both the Custom All-Ceramic and Proprietary Tabs and the Custom Metal-Ceramic Samples

		∆L*	∆a*	∆b*	∆E
2mm AC v 2 mm MC					
	B1	-5.25	0.22	-2.29	**4.13**
	A3	-1.76	0.20	-1.92	**1.82**
	D4	0.90	1.97	2.38	**2.74**
Shade Tab v 2 mm MC					
	B1	0.83	0.38	1.53	**1.38**
	A3	0.95	1.88	1.40	**2.38**
	D4	8.76	-0.40	2.74	**7.51**

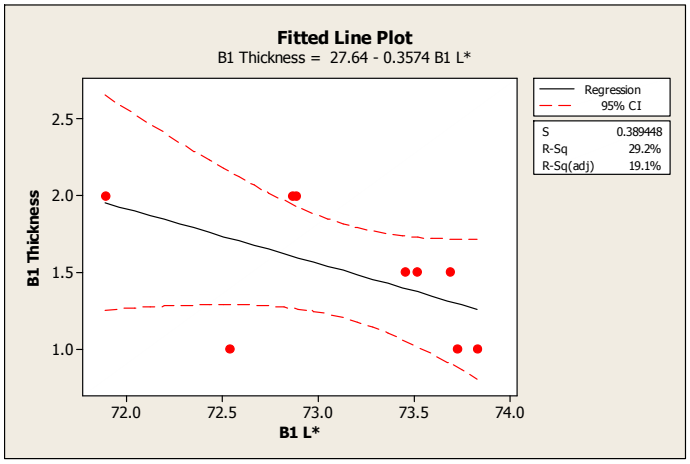
The linear regression analysis was used to assess the relationship between colour (L*a*b* co-ordinates) and the ceramic thickness of metal-ceramic samples (Figures 5.18, 5.19 and 5.20 for shades B1, A3 and D4 respectively). These results indicated that thickness-dependent colour changes were present. As thickness increases both L* and b* tended to decrease. The colour differences between each of thickness group would have been perceptible:

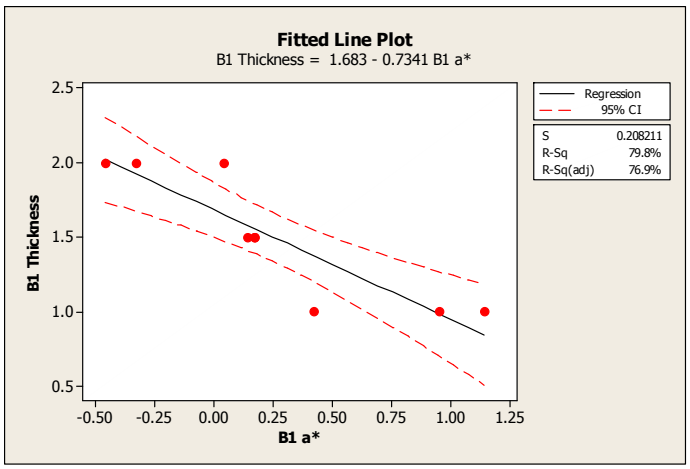
a. L* tended to decrease (tabs were darker) as the thickness increased. Linear regression analysis found a correlation between ceramic thickness and L*. This was most apparent for D4 (R-Sq=97.3), the darkest shade in this study: as dentine ceramic thickness increased by 0.5 mm the L* decreased by around 1.5 units. B1 showed the least correlation (R-Sq=29.2) whilst A3 was intermediate (R-Sq=77.4) but closer to D4.
b. Samples tended to become slightly less red (smaller a*) as thickness increased, however, this was a smaller change than the other colour co-ordinates. The mean of the mean values indicated a decrease of around 0.6 a* units per 0.5 mm of additional dentine ceramic. Linear regression found a strong correlation between the a* values and ceramic thickness: R-Sq values

were again highest for D4 (92.3) whilst being smaller for B1 and A3, 79.8 and 90.2 respectively.

c. Increasing thickness produced less yellow B1 and A3 tabs but did not influence D4 consistently. The correlation between thickness and b* was less strong, but best for A3 (R-Sq=73.3).

Figure 5.18. Linear Regression of Mean L*a*b* Co-ordinates and Ceramic Thickness of Custom Metal-Ceramic Tabs (Shade B1)





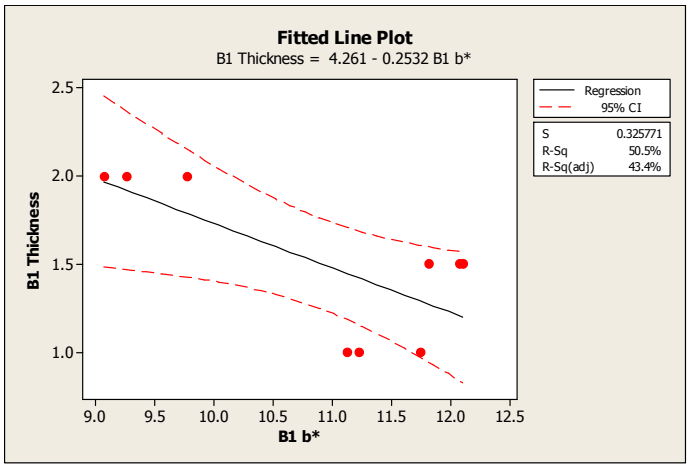
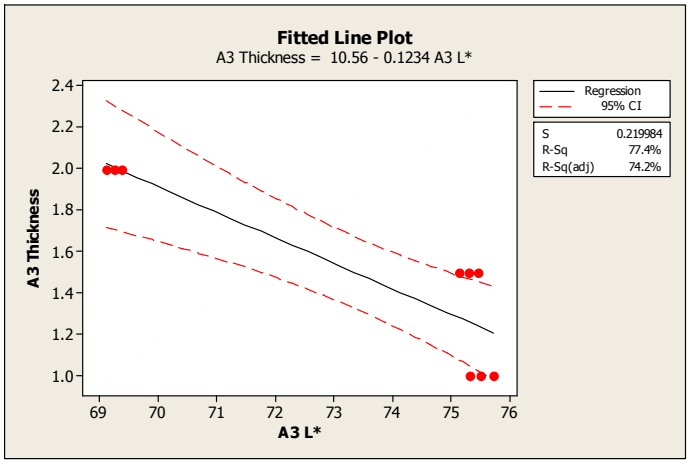
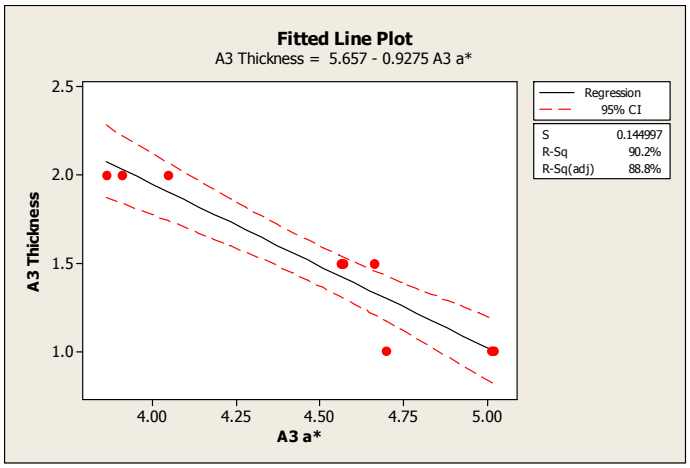


Figure 5.19. Linear Regression of Mean L*a*b* Co-ordinates and Ceramic Thickness of Custom Metal-Ceramic Tabs (Shade A3)





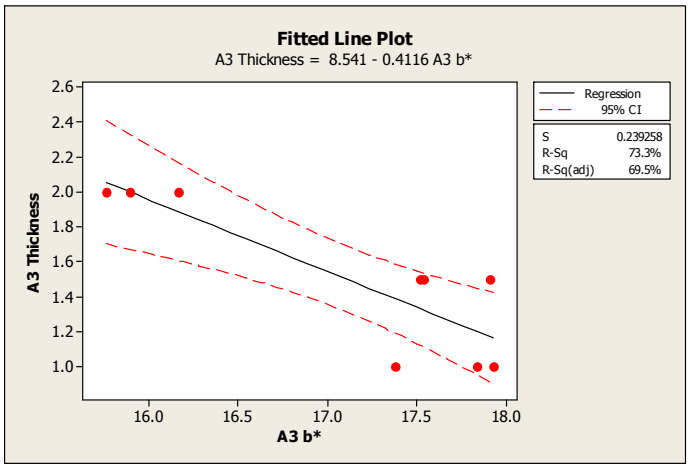
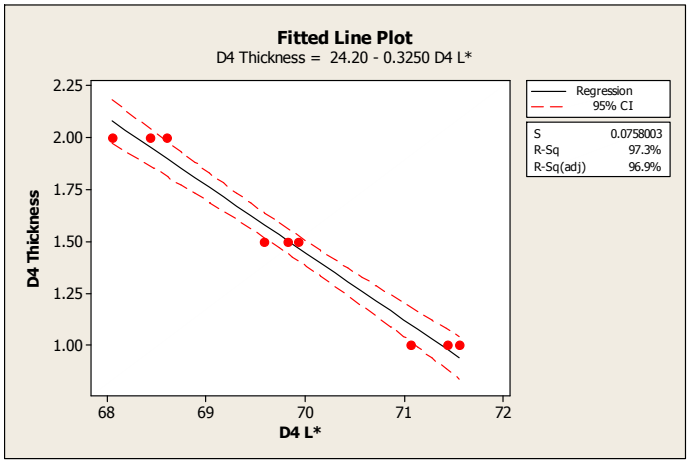
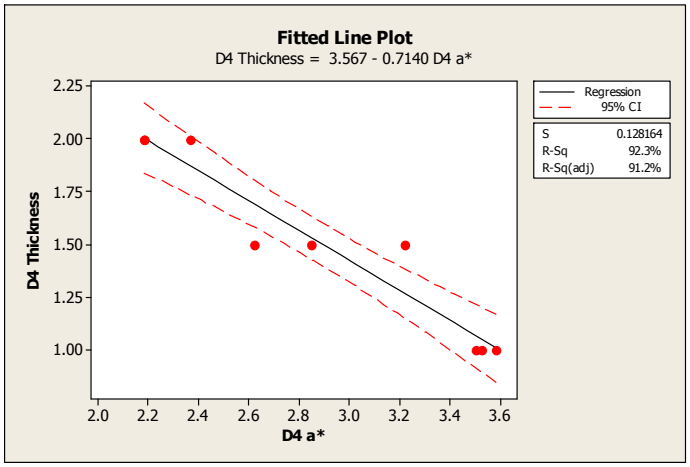
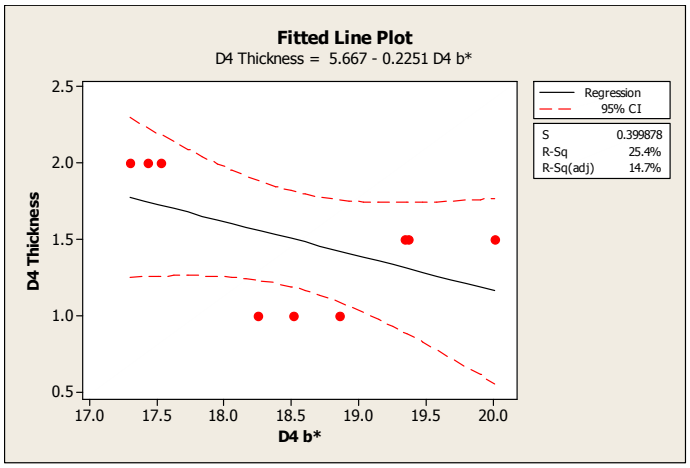


Figure 5.20. Linear Regression of Mean L*a*b* Co-ordinates and Ceramic Thickness of Custom Metal-Ceramic Tabs (Shade D4)







5.2.6 The Fabrication and Spectrophotometric Consistency of Metal-Ceramic Samples (Expt. 4C)

Consistency of Fabrication of Tabs from the Same Group

Table 28 indicated that there were small colour differences (ΔE_{00}) between tabs of the same thickness and shade. The colour difference between samples within groups was shade and, to a lesser extent, thickness dependent. The thinner and B1 tabs were more susceptible to increased colour differences.

Table 28 Differences in ΔE_{00} , using Mean L*a*b* Co-ordinates, between Tabs of the Same Shade and Thickness

		Shade B1		Shade A3		Shade D4	
Ceramic Thickness	**Tabs Compared**	**Day 1 ΔE**	**Day 2 ΔE**	**Day 1 ΔE**	**Day 2 ΔE**	**Day 1 ΔE**	**Day 2 ΔE**
1 mm	1 to 2	1.19	0.86	0.40	0.96	0.52	0.14
	1 to 3	1.06	1.09	0.40	0.10	0.21	0.31
	2 to 3	0.97	1.16	0.56	0.86	0.34	0.26
1.5 mm	1 to 2	0.26	0.15	0.25	0.92	0.31	0.63
	1 to 3	0.18	0.38	0.25	0.15	0.49	0.25
	2 to 3	0.13	0.45	0.30	0.86	0.74	0.69
2 mm	1 to 2	0.71	0.43	0.16	0.16	0.38	0.40
	1 to 3	1.06	0.95	0.31	0.20	0.35	0.20
	2 to 3	0.78	0.57	0.27	0.19	0.46	0.31

The B1 tabs had statistically significant larger colour differences than the other shades ($p<0.05$) which may be accounted for by this shade's higher Value (L*) and lower Chroma (a* and b*) being more sensitive to fabrication variables.

The mean colour difference (ΔE_{00}) between the 1 mm tabs of all shades was greater than for the thicker tabs ($p<0.05$). The reasons for this were discussed in the all-ceramic section above. In addition, small variations in the opaque layer (thickness and surface) may have contributed.

Consistency of Spectrophotometric Measurements

The coefficients of variation of the colour measurements were calculated for the metal-ceramic tabs. Several values of >1% were found for the a* colour co-ordinates of shade B1 (Table 24). Calculations of Δe were not required as these variations were extremely small. The maximum variation of the a* component was 0.03 units across each data set which was not large enough to influence subsequent calculations. Repeatability was therefore slightly improved, implying that colour measurement of dental samples can be improved by having an opaque backing.

The colour differences (ΔE_{00}) between days 1 and 2 for these metal-ceramic tabs were also small (Table 29). The source of these differences would have due to day-to-day spectrophotometer differences (possibly due to slight calibration differences), or more possibly small positioning differences. However, the mounting protocol should be prevented positioning errors from having a substantial influence.

Table 29 Colour Differences (ΔE_{00}), using Mean L*a*b* Co-ordinates, between Days 1 & 2 of Custom Metal-Ceramic Tabs of Varying Thicknesses and Shades

	TAB	ΔE_{00}		ΔE_{00}		ΔE_{00}
1mm B1	**1**	0.24	**1mm A3**	0.23	**1mm D4**	0.23
	2	0.27		0.58		0.38
	3	0.32		0.42		0.25
1.5mm B1	**1**	0.17	**1.5mm A3**	0.35	**1.5mm D4**	0.20
	2	0.27		0.74		0.41
	3	0.15		0.14		0.42
2mm B1	**1**	0.60	**2mm A3**	0.50	**2mm D4**	0.32
	2	0.97		0.28		0.20
	3	0.19		0.29		0.32

5.2.7 The Effects of the Type of Sample on Spectrophotometric Measurements

Comparisons between experiments 4A, 4B and 4C were calculated from previously discussed Day 1 measurements. It is unfortunate that no standard ceramic sample was available for bench-marking measurements. This would have allowed perhaps a more quantified analysis of these colour measurements. If the colour of the unaltered shade tab is regarded as the closest item to a gold standard, then following trends were evident:

1. For custom-made all-ceramic tabs of shade A3 and D4, the 5 mm thick tabs were significantly closer to the colour of their respective unaltered shade tabs than the other thicknesses of tabs. However, the 2 mm thick B1 tabs were substantially closer to the colour of the shade tab than the other thicknesses (Figure 5.21). The colour differences between the unaltered proprietary tabs and the 2 and 4 mm custom-made all-ceramic tabs were recorded in Table 23, with the magnitude of these being shade dependent. The lightness (L*) and yellowness (b*) of the custom all-ceramic tabs were higher than the shade tabs but the magnitude varied with shade. There was little variation in red-greenness (a*) of the shade B1 tabs. However, the A3 custom tabs had higher a* co-ordinates than the shade tabs with the opposite being true for the D4 tabs.
2. For custom-made metal-ceramic tabs, the 2 mm thick tabs were significantly closer to the colour of their respective unaltered shade tabs than the other thicknesses of tabs (Figure 5.22). The metal-ceramic tabs were lighter (higher L*) and more yellow (higher b*) than the proprietary tabs, with the D4 having the largest colour differences (ΔE_{00}). The direction of change for

the a* values was shade dependent. The metal and opaque ceramics had effects on the colour of ceramic but the direction of this was related to the shade tested. The darkest and yellowiest shade (D4) was affected in a different manner than the other shades.

For both the all-ceramic and metal-ceramic tabs, the colour difference between the tab closest to the shade tab would have been clinically perceptible under ideal viewing conditions.

The metal-backed B1 and A3 tabs were darker (lower L*) and less yellow (lower b*) than their all-ceramic counterparts, however, the redness values changed little. The D4 tabs had L* and b* trends in the opposite direction. A substantial reddening (1.97 a* units) was seen when a metal backing was used with the D4 tabs. This reddening was in the same direction as the other shades but was significantly larger. Comparing the custom-made all-ceramic and metal-ceramic tabs, the L* changes and therefore the colour differences (ΔE_{00}) were substantially larger for the B1 tabs than other shades.

Figure 5.21. Comparison of the Colour Co-ordinates of Proprietary Shade Tabs and Custom-made All-Ceramic Tabs of Varying Thicknesses

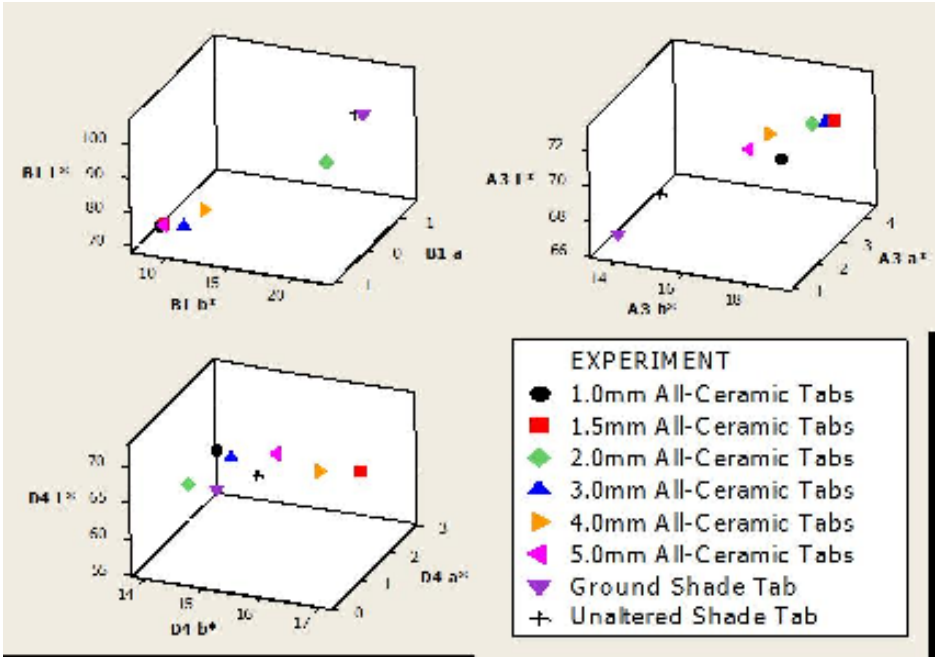
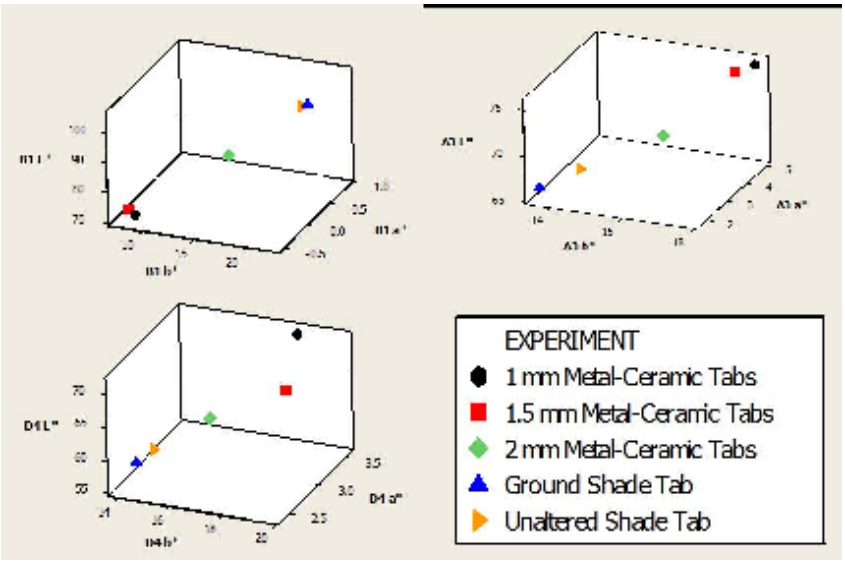


Figure 5.22. Comparison of the Colour Co-ordinates of Proprietary Shade Tabs and Custom-made Metal-Ceramic Tabs of Varying Thicknesses



5.3 The Effects of Metal Treatment and Opaque Ceramic on Spectrophotometric Measurements (Expt. 5)

This part of the investigation made colour measurements of metal alone and metal covered with opaque ceramic to identify the effect of these stages in the fabrication process on the colour co-ordinates. This may help to interpret the results of other experiments.

Table 30 recorded a summary of the mean colour co-ordinates (L*a*b*) of three tabs removed at different stages in the fabrication process.

Table 30 Mean Colour Co-ordinates of Metal and Opaque Ceramic Tabs

		L*	a*	b*
Sandblasted		46.63	0.84	3.17
Steam cleaned		54.99	0.52	2.29
Oxidised		33.67	-0.08	4.16
Wash Opaque		69.91	10.71	32.08
Shade B1 opaque		80.53	1.59	9.59
Shade A3 opaque		79.38	4.94	14.55
Shade D4 opaque		78.64	2.82	14.79

The underlying nickel-chrome and subsequent surface treatments were in the grey-black region of colour space. Steam cleaning and oxidisation had a significant effect on the colour but, more importantly, provided baseline co-ordinates (Table 30).

The addition of the Vita wash opaque ceramic to the metal tabs caused a substantial increase in the L*, a* and b* values: the most significant effect of opaque was to make the tabs extremely yellow. One application of any of the shades of shade-designated opaque ceramic caused the tabs to become visibly lighter, redder and substantially less yellow compared to the tabs with wash opaque. This indicated the

yellowness of metal-ceramic samples was due to the opaque ceramics and that dentine ceramics try to diminish these effects.

The variation between the shade opaque tabs was primarily due to changes in a* and b* (redness and yellowness), with little difference between the shades with regard to L* (lightness). This indicated that differences in L* between the shades of a metal-ceramic restorations/samples would be due to the dentine ceramic and not the opaque.

Table 31 recorded the colour differences between the same shades of 2 mm metal-ceramic tabs (expt. 4C) and those of the tabs with only the shade-designated opaque ceramic (expt. 5).

Table 31 Colour Differences between Opaque Samples (Expt. 5) and 2 mm Metal-Ceramic Tabs (Expt. 4C)

	∆L*	∆a*	∆b*	∆E
B1	-7.99	-1.84	0.17	**6.26**
A3	-10.23	-1.00	1.39	**7.70**
D4	-10.28	-0.57	2.63	**7.85**

Following the addition of dentine ceramic, the tabs were obviously darker, less red and more yellow. However, the majority of the change was due to changes in L* (7.99, 10.23, 10.28 for B1, A3 and D4 respectively).

5.4 The Effects of the Number of Ceramic Firings on Spectrophotometric Measurements (Expt. 6)

A summary of the results for experiment 6A is presented in Tables 32 to 34 and in 3D charts (Figures 5.23 to 5.25).

The colour differences, using mean co-ordinates of all tabs from each group, between tabs fired a different number of times were recorded in Table 35. Repeated firings altered the colour co-ordinates measured, but the colour differences were generally small. In general, as the number of firings increased the lightness (L*) increased whilst the a* and b* values decreased with the A3 tabs being affected more than the other shades. The colour difference between the groups increased as the total firing time increased. However, repeated firings did not have a linear effect on the colour co-ordinates as bigger differences were usually found between the 3 and 4 firings group than those between the 2 and 3 firings. These differences, between the size of the colour differences between the firing groups, were not statistically significant ($p>0.05$).

a. For shades B1 and A3, as the number of firings increased the L* values increased with statistically significant differences between the tabs fired 2 and 4 times ($p<0.05$ and $p<0.001$). No trends or significant differences were found between the L* of the D4 groups.
b. The a* values were generally lower as the number of firing cycles increased and there were statistical differences between tabs fired 2 and 3, 2 and 4 as well as 3 and 4 times of all shades except between B1 tabs fired 2 and 3 ($p>0.05$) and D4 tabs fired 3 and 4 times ($p>0.05$).

c. The yellowness (b*) generally decreased as the number of firings increased with statistically significant differences between all groups of shade A3 ($p<0.05$). However, no statistical differences were found for the shade B1 and D4 tabs ($p>0.05$).

The magnitude of the colour differences were small and were influenced by measurement discrepancies and the large confidence intervals due to the small sample size. D4 may have been more resistant to changes as a result of increased firing. Although slightly larger colour differences were found between the D4 tabs of the same group which may have prevented statistical differences from being identified (section 6.4.8.2). The results showed that repeated firing had an effect on the colour of the ceramic produced and the colour differences between each group would just be perceptible using the strictest criteria. However, the clinical effect would minimal.

Table 32 Mean (±SD) Colour Co-ordinates (L*a*b*) + Coefficients of Variation % (CV) for Custom Metal-Ceramic Samples with varying the Numbers of Firing Cycles (Shade B1)

			L*			a*			b*		
			Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
2 Firings	Day 1	Tab 1	**72.84**	0.00	0.00%	**0.55**	0.01	0.91%	**10.18**	0.01	0.06%
		Tab 2	**72.85**	0.00	0.00%	**0.85**	0.01	0.60%	**11.17**	0.01	0.08%
	Day 2	Tab 1	**72.89**	0.01	0.01%	**0.61**	0.01	0.90%	**10.27**	0.01	0.11%
		Tab 2	**72.83**	0.00	0.01%	**0.73**	0.00	0.44%	**10.96**	0.01	0.12%
3 Firings	Day 1	Tab 1	**73.36**	0.00	0.00%	**0.75**	0.00	0.57%	**10.76**	0.01	0.06%
		Tab 2	**73.33**	0.00	0.00%	**0.67**	0.00	0.61%	**10.01**	0.01	0.07%
	Day 2	Tab 1	**73.39**	0.01	0.01%	**0.83**	0.01	0.63%	**10.85**	0.01	0.08%
		Tab 2	**72.74**	0.00	0.01%	**0.75**	0.01	0.67%	**10.28**	0.01	0.08%
4 Firings	Day 1	Tab 1	**73.31**	0.00	0.01%	**0.47**	0.00	0.96%	**10.32**	0.01	0.06%
		Tab 2	**73.81**	0.00	0.01%	**0.34**	0.01	2.09%	**9.27**	0.01	0.07%
	Day 2	Tab 1	**73.28**	0.00	0.01%	**0.47**	0.00	0.81%	**10.22**	0.01	0.07%
		Tab 2	**73.21**	0.00	0.01%	**0.35**	0.01	1.46%	**9.32**	0.01	0.08%

Figure 5.23. Mean L*a*b* Co-ordinates of Custom Metal-Ceramic Samples after Varying the Number of Firing Cycles (Shade B1, Day 1)

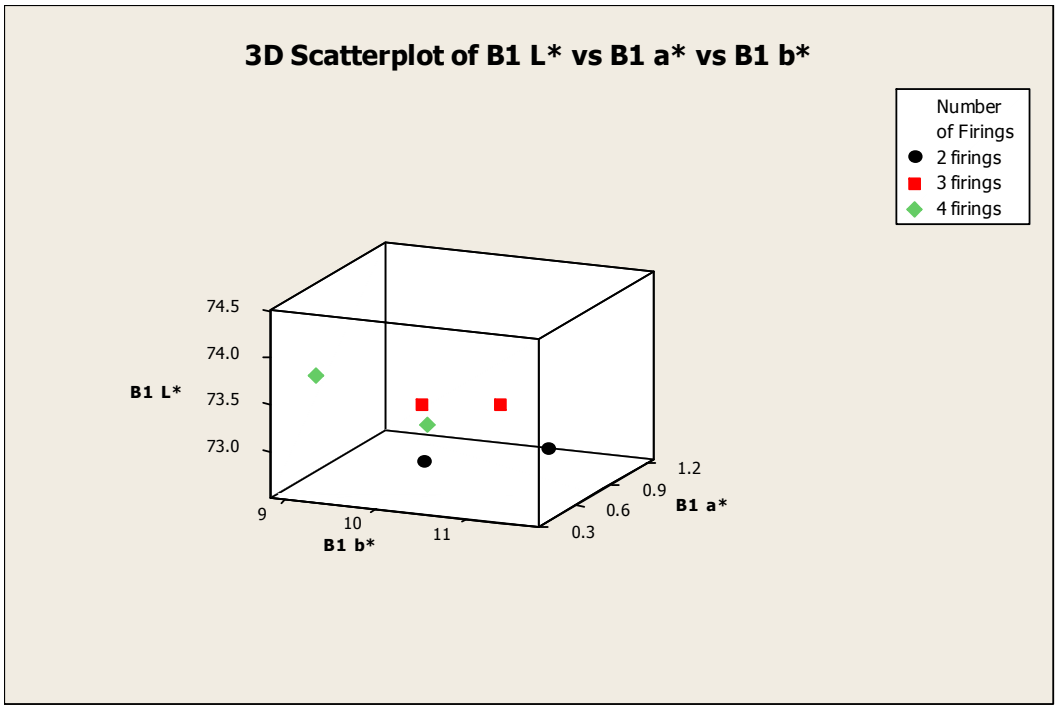


Table 33 Mean (±SD) Colour Co-ordinates (L*a*b*) + Coefficients of Variation % (CV) for Custom Metal-Ceramic Samples with varying the Numbers of Firing Cycles (Shade A3)

			L*			a*			b*		
			Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
2 Firings	Day 1	Tab 1	**70.57**	0.01	0.01%	**4.25**	0.01	0.13%	**18.42**	0.01	0.04%
		Tab 2	**70.14**	0.00	0.01%	**4.04**	0.01	0.14%	**18.51**	0.02	0.08%
	Day 2	Tab 1	**70.65**	0.01	0.01%	**4.25**	0.01	0.12%	**18.20**	0.01	0.05%
		Tab 2	**70.15**	0.00	0.01%	**4.05**	0.01	0.13%	**18.42**	0.01	0.04%
3 Firings	Day 1	Tab 1	**71.52**	0.01	0.01%	**3.60**	0.01	0.14%	**15.86**	0.01	0.04%
		Tab 2	**71.31**	0.01	0.02%	**3.31**	0.01	0.19%	**15.82**	0.03	0.17%
	Day 2	Tab 1	**71.56**	0.00	0.01%	**3.60**	0.00	0.13%	**15.74**	0.01	0.05%
		Tab 2	**71.71**	0.01	0.01%	**3.28**	0.01	0.17%	**15.63**	0.03	0.16%
4 Firings	Day 1	Tab 1	**71.79**	0.01	0.01%	**3.39**	0.01	0.15%	**16.34**	0.01	0.04%
		Tab 2	**71.92**	0.00	0.00%	**3.48**	0.00	0.14%	**16.21**	0.01	0.04%
	Day 2	Tab 1	**71.71**	0.02	0.03%	**3.45**	0.00	0.12%	**16.38**	0.01	0.05%
		Tab 2	**71.99**	0.01	0.01%	**3.42**	0.01	0.16%	**16.24**	0.01	0.08%

Figure 5.24. Mean L*a*b* Co-ordinates of Custom Metal-Ceramic Samples after Varying the Number of Firing Cycles (Shade A3, Day 1)

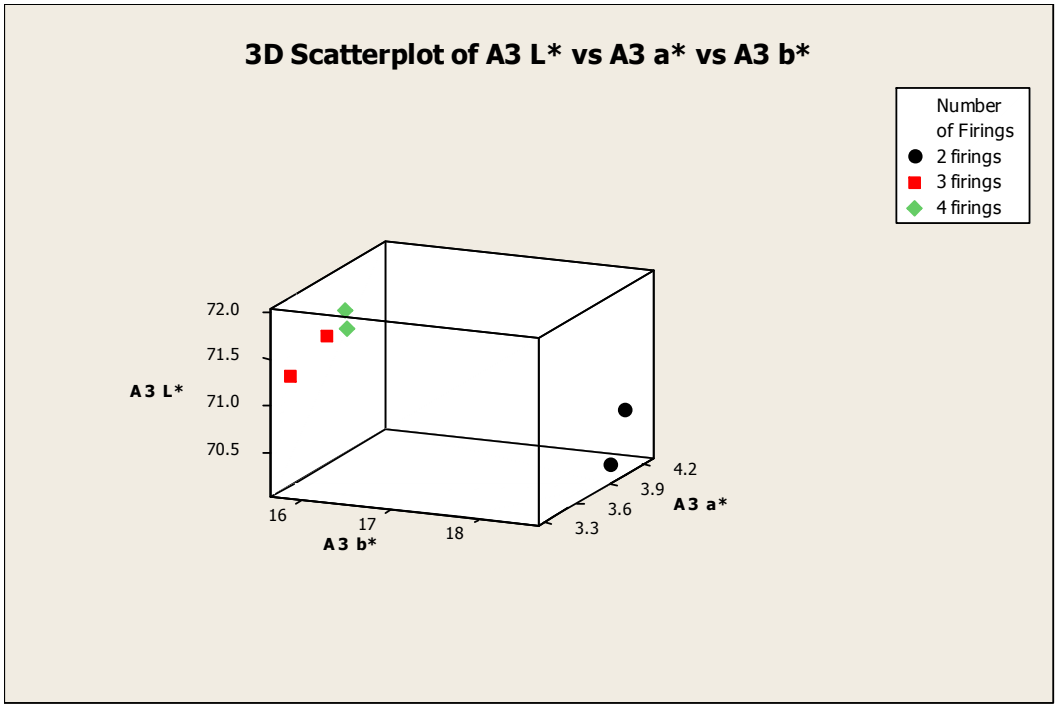


Table 34 Mean (±SD) Colour Co-ordinates (L*a*b*) + Coefficients of Variation % (CV) for Custom Metal-Ceramic Samples with varying the Numbers of Firing Cycles (Shade D4)

			Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
2 Firings	*Day 1*	*Tab 1*	**69.08**	0.02	0.03%	**2.14**	0.01	0.29%	**17.78**	0.05	0.28%
		Tab 2	**68.93**	0.02	0.03%	**2.08**	0.01	0.25%	**17.60**	0.04	0.20%
	Day 2	*Tab 1*	**69.37**	0.02	0.03%	**2.09**	0.01	0.26%	**17.92**	0.03	0.18%
		Tab 2	**69.16**	0.03	0.04%	**2.14**	0.01	0.28%	**17.01**	0.06	0.34%
3 Firings	*Day 1*	*Tab 1*	**68.71**	0.00	0.01%	**1.84**	0.01	0.28%	**17.10**	0.01	0.04%
		Tab 2	**70.37**	0.01	0.01%	**1.89**	0.01	0.33%	**16.17**	0.01	0.08%
	Day 2	*Tab 1*	**68.86**	0.00	0.00%	**1.82**	0.00	0.27%	**16.75**	0.01	0.05%
		Tab 2	**69.68**	0.01	0.01%	**2.08**	0.01	0.24%	**17.48**	0.01	0.08%
4 Firings	*Day 1*	*Tab 1*	**69.45**	0.00	0.01%	**1.39**	0.01	0.40%	**15.37**	0.01	0.04%
		Tab 2	**68.00**	0.00	0.00%	**1.82**	0.01	0.30%	**17.25**	0.01	0.05%
	Day 2	*Tab 1*	**69.08**	0.00	0.00%	**1.49**	0.01	0.34%	**16.03**	0.01	0.09%
		Tab 2	**68.08**	0.00	0.01%	**1.81**	0.00	0.27%	**17.23**	0.01	0.06%

Figure 5.25. Mean L*a*b* Co-ordinates of Custom Metal-Ceramic Samples after Varying the Number of Firing Cycles (Shade D4, Day 1)

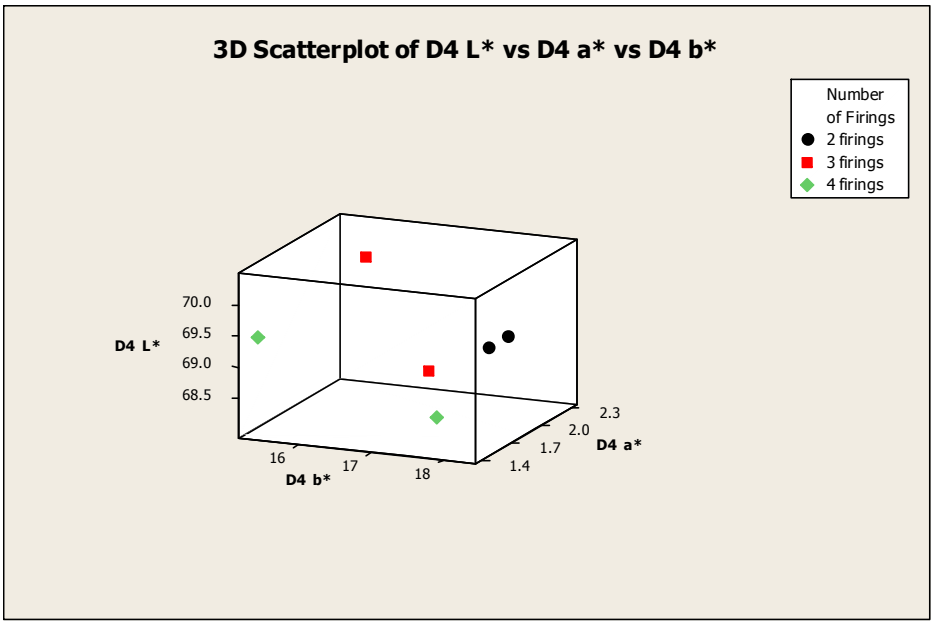
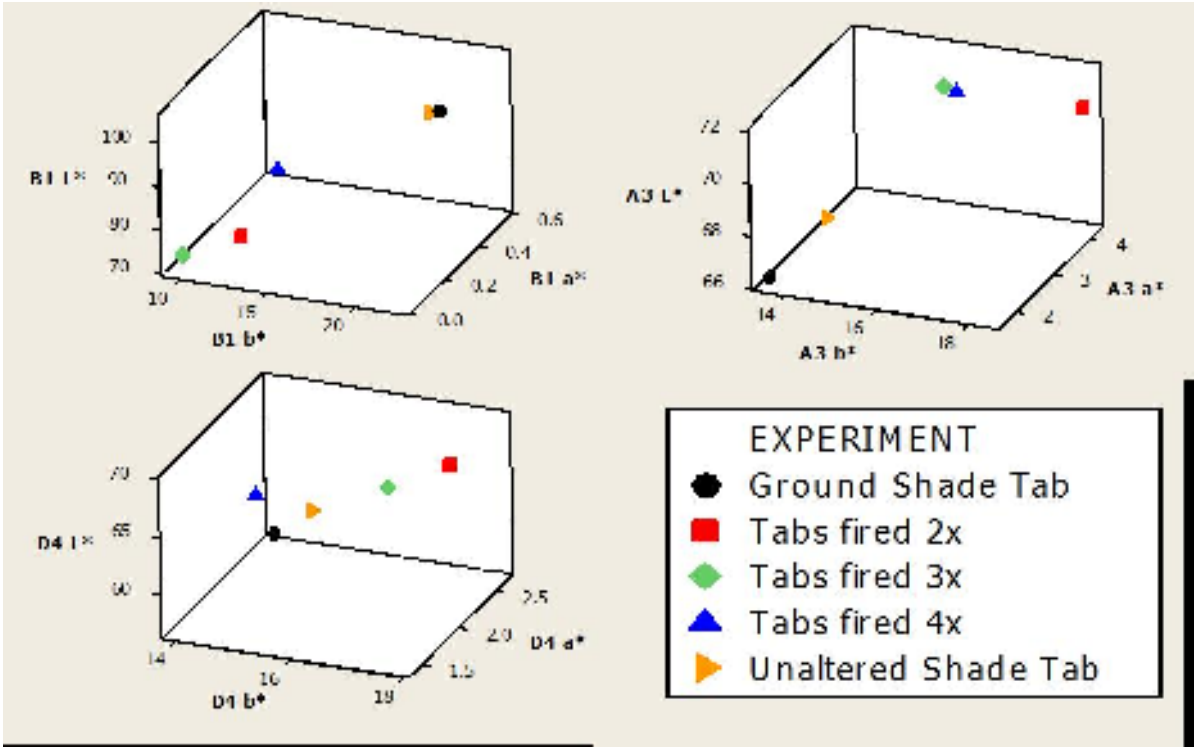


Table 35 Differences in ΔE_{00}, using Mean L*a*b* Co-ordinates, between Three Shades of Tab after a Different Number of Firing Cycles

B1				
Number of Firings	**∆L***	**∆a***	**∆b***	**ΔE_{00}**
2 v 3	0.36	0.05	-0.17	**0.30**
3 v 4	0.19	-0.34	-0.70	**0.66**
2 v 4	0.55	-0.29	-0.87	**0.81**
A3				
Number of Firings	**∆L***	**∆a***	**∆b***	**ΔE_{00}**
2 v 3	1.14	-0.70	-2.62	**1.78**
3 v 4	1.47	-0.72	-2.09	**1.71**
2 v 4	0.33	-0.02	0.53	**0.41**
D4				
Number of Firings	**∆L***	**∆a***	**∆b***	**ΔE_{00}**
2 v 3	0.27	-0.20	-0.70	**0.48**
3 v 4	-0.76	-0.28	-0.41	**0.71**
2 v 4	-0.49	-0.48	-1.11	**0.88**

For the A3 and D4 tabs, as the number of firings increased (up to 4 times) the colour of the tabs got closer to the colour of the shade tabs (Figure 5.26). For the B1 tabs, the tabs fired 4 times were the closest colour match to the shade tab. However, the tabs fired twice were closer than the tabs fired three times.

Figure 5.26. Comparison of the Colour Co-ordinates of Proprietary Shade Tabs and Tabs Fired a Varying Number of Times



5.4.1 The Fabrication and Spectrophotometric Consistency of Metal-Ceramic Samples Fired a Varying Number of Times (Expt. 6)

Consistency of Fabrication of Tabs from the Same Group

The repeatability of the measurements within in each data set were discussed in section 4.4.1: instrument drift in this experiment was discussed and a second set of tabs were fabricated and measured.

No colour difference (ΔE_{00}) any one tab between days 1 and 2 was >1 unit (Table 36). Tabs of shades B1 (n=2) and D4 (n=3) had differences >0.4 (perceptibility threshold). This represented good repeatability across the tabs that had been fired

multiple times, however the 2nd tab of shade D4 in the 3 firing group had increased variation (0.93). However, these differences were not significant statistically.

Table 36 Differences in ΔE_{00}, using Mean L*a*b* Co-ordinates, between Days 1 and 2 for Three Different Shades of Metal-Ceramic Tab after a Different Number of Firing Cycles

Number of firings	2		3		4	
	TAB 1	*TAB 2*	*TAB 1*	*TAB 2*	*TAB 1*	*TAB 2*
Shade B1	0.10	0.20	0.12	0.49	0.07	0.45
Shade A3	0.14	0.06	0.08	0.33	0.09	0.09
Shade D4	0.25	0.40	0.23	0.93	0.49	0.07

The samples in each group of the same shade and thickness were fired an equal number of times. Shade differences existed: the mean colour difference between the A3 tabs (0.31 ΔE_{00} units) was lower than both the B1 and D4 tabs (0.65 and 0.94 units). However, statistical analysis only found a difference in the size of the colour differences between the tabs between the A3 tabs and the others ($p<0.05$). There was no difference found between shades B1 and D4 ($p>0.05$).

It was surmised that increasing the number of firings may have reduced the size of colour differences between tabs, from the same group, as the increased sintering time would 'even-out' small differences in firings. However, statistical analysis found no difference ($p>0.05$).

5.5 The Effects of the Operator on Spectrophotometric Measurements of Metal-Ceramic Samples (Expt. 7)

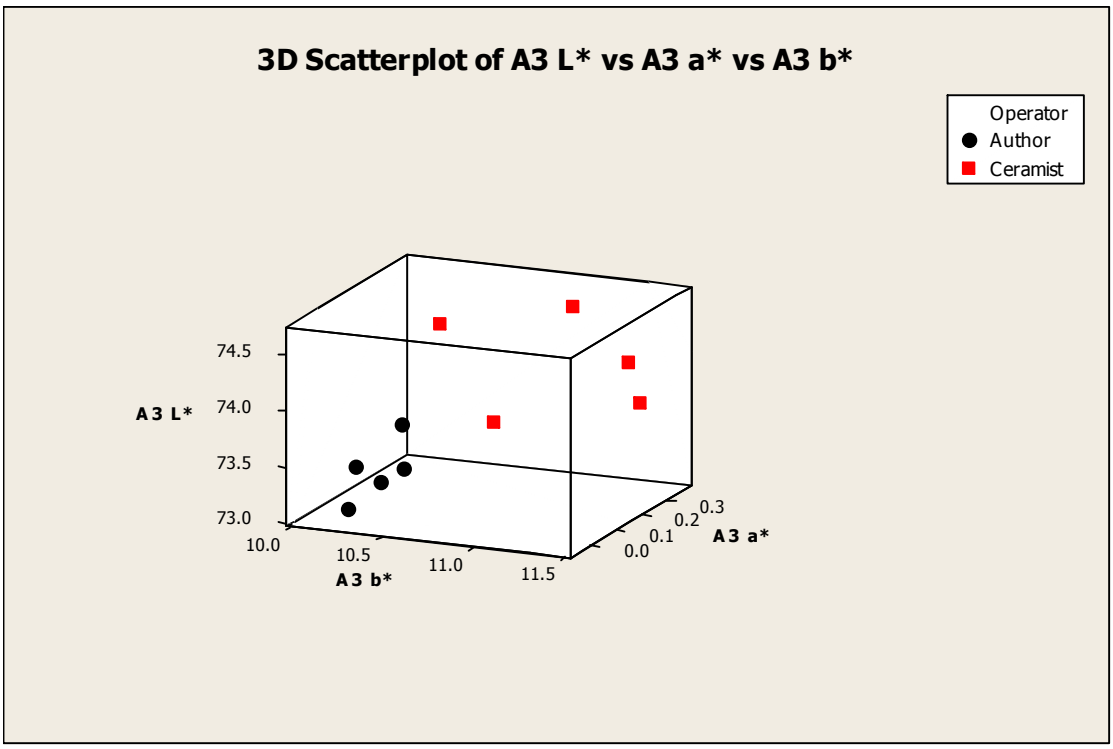
Specific variations in the investigator's ceramic build-up technique may have influenced the colours measured. Therefore, in addition to the investigator, an experienced ceramist was used in this experiment for comparative purposes.

Table 37 and Figure 5.27 recorded a summary of the results for both operators and Interestingly, the ceramist's tabs were distributed over a larger over of colour space than the investigator's.

Table 37 Effects of Operator on Mean (±SD) Colour Co-ordinates (L*a*b*) + Coefficients of Variation % (CV)

	INVESTIGATOR								
	L*			**a***			**b***		
	Mean	**SD**	**CV**	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**
Tab 1	**73.37**	0.01	0.02%	**0.05**	0.00	10.55%	**10.17**	0.02	0.19%
Tab 2	**73.14**	0.00	0.01%	**-0.06**	0.01	-9.22%	**10.27**	0.01	0.09%
Tab 3	**73.37**	0.00	0.01%	**0.07**	0.00	5.57%	**10.41**	0.01	0.07%
Tab 4	**73.26**	0.00	0.00%	**0.04**	0.00	11.36%	**10.31**	0.01	0.08%
Tab 5	**73.71**	0.01	0.01%	**0.10**	0.00	4.38%	**10.35**	0.01	0.10%
	CERAMIST								
	L*			**a***			**b***		
	Mean	**SD**	**CV**	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**
Tab 1	**73.83**	0.00	0.00%	**0.29**	0.00	1.69%	**11.39**	0.01	0.05%
Tab 2	**74.65**	0.00	0.01%	**0.27**	0.00	1.79%	**11.05**	0.01	0.06%
Tab 3	**74.31**	0.00	0.00%	**0.30**	0.00	1.61%	**10.28**	0.01	0.08%
Tab 4	**73.71**	0.00	0.00%	**0.16**	0.00	2.50%	**10.77**	0.01	0.06%
Tab 5	**74.05**	0.01	0.01%	**0.37**	0.00	0.87%	**11.22**	0.01	0.06%

Figure 5.27. Effects of Operator on Mean L*a*b* Co-ordinates of Custom Metal-Ceramic Samples



The colour differences between the investigator's tabs had fewer perceptible colour differences. Table 38 recorded that the investigator's tabs had a lower mean (0.24±0.11 ΔE_{00}) compared to the ceramist (0.57±0.17 ΔE_{00}) and these differences were highly significant ($p<0.001$).

Table 38 Differences in ΔE_{00}, using Mean L*a*b* Co-ordinates, between the Tabs from the same Operator

Investigator					
	1	**2**	**3**	**4**	**5**
1	x	0.23	0.17	0.13	0.29
2	x	x	0.25	0.16	0.47
3	x	x	x	0.11	0.26
4	x	x	x	x	0.34
5	x	x	x	x	x
Ceramist					
	1	**2**	**3**	**4**	**5**
1	x	0.64	0.83	0.46	0.23
2	x	x	0.58	0.73	0.47
3	x	x	x	0.59	0.67
4	x	x	x	x	0.48
5	x	x	x	x	x

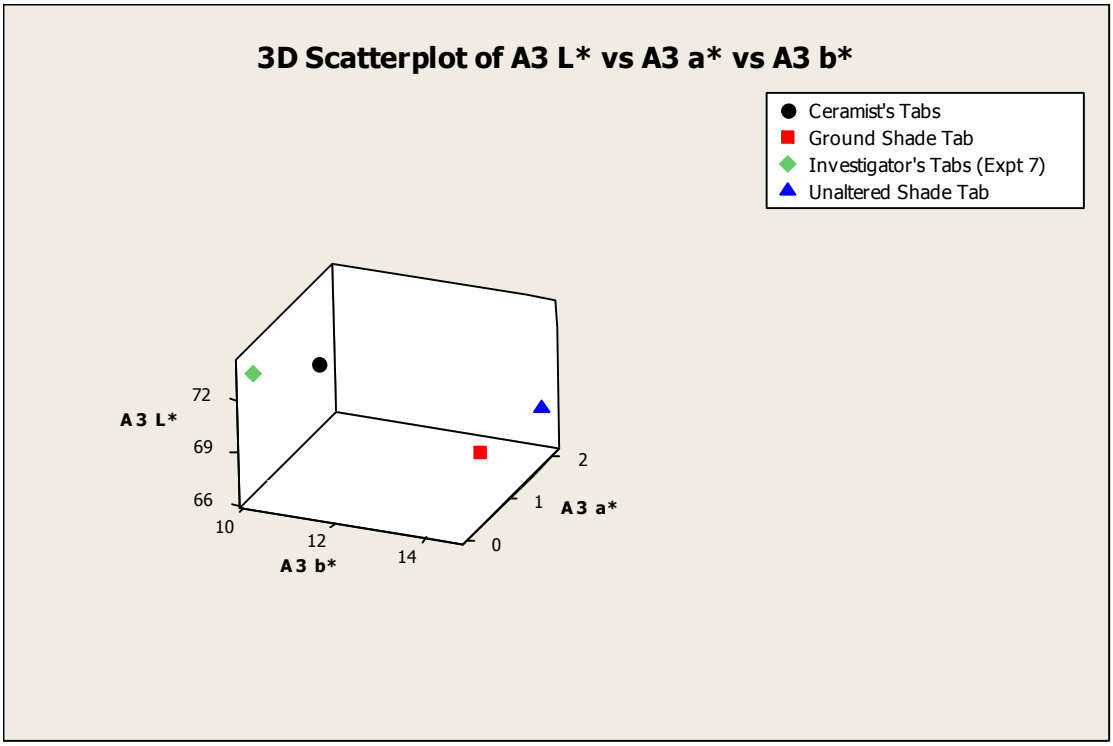
Table 39 recorded the colour differences (ΔE_{00}) between tabs produced by different operators. All except one of the 25 comparisons gave a perceptible colour difference with a mean for the table of 0.83 (±0.26) ΔE_{00} units. Six comparisons had a colour difference of more than one unit, all of which occurred when each operator's second tab was used as the standard sample in the comparison. The authors tabs had significantly smaller L* (≈0.7 units), a* (≈0.25 units) and b* values (≈0.6 units). However, the mean total colour difference (0.77) between the tabs would probably not have been visible clinically.

Table 39 Differences in ΔE_{00}, using Mean L*a*b* Co-ordinates, between the Tabs from each of the 2 different Operators

		Ceramist Tab's				
		1	**2**	**3**	**4**	**5**
Investigator Tab's	**1**	0.95	1.16	0.78	0.51	0.97
	2	1.02	1.31	0.99	0.61	1.09
	3	0.79	1.08	0.77	0.37	0.84
	4	0.90	1.18	0.85	0.48	0.95
	5	0.74	0.87	0.52	0.29	0.73

When the colour co-ordinates of the samples were compared to shade tabs, the ceramist's tabs were closer to the colour of the shade tab (Figure 5.28).

Figure 5.28. Comparison of the Colour Co-ordinates of Proprietary Shade Tabs and Tabs from Different Operators



Despite similar instructions being given to both operators, differences in the porcelain build-up technique must have existed to produce these results. It was surmised that the amount of condensation varied between the operators causing the changes in colour. Unfortunately, the porosity of these samples could not be assessed. The next two experiments assessed the affects of condensation on porosity and colour.

5.6 The Effects of Method of Varying Ceramic Condensation on Spectrophotometric Measurements (Expt. 8)

The comparison of the colours produced by two different individuals carrying out the same technical procedure was interesting. It seemed logical to investigate the effect of the method of condensation on the colour co-ordinates of the ceramic samples. A standard method of condensation had been used in experiments 1 through 7. Three more methods were included in expt. 8 to allow further comparisons and the effect on colour was investigated. The degree of condensation differed between each group: blot drying was likely to have produced samples that were relatively poorly condensed whilst ultrasonic condensation plus blot drying produced the best condensed. The other two methods were considered to be intermediate.

The data were displayed in 3D Charts and the differences in colour co-ordinates (L*a*b*) between each condensation group were calculated for each shade: B1 (Figures 5.29 and Table 40), A3 (Figures 5.30 and Table 41) and D4 (Figures 5.31 and Table 42). This data indicated that the method of condensation of the ceramic slurry before firing had an influence on the final colour of each of the three shades of the metal-ceramic tabs but the magnitude and direction of the effects were shade dependent. A summary of the colour co-ordinates and the coefficients of variation for experiment 8 was recorded in Appendices G to R. The results of the ANOVA analyses between the condensation groups for shades B1, A3 and D4 were recorded in Tables 43, 44 and 45 respectively.

Figure 5.29. Effects of Condensation Technique on Mean L*a*b* Colour Co-ordinates (Shade B1)

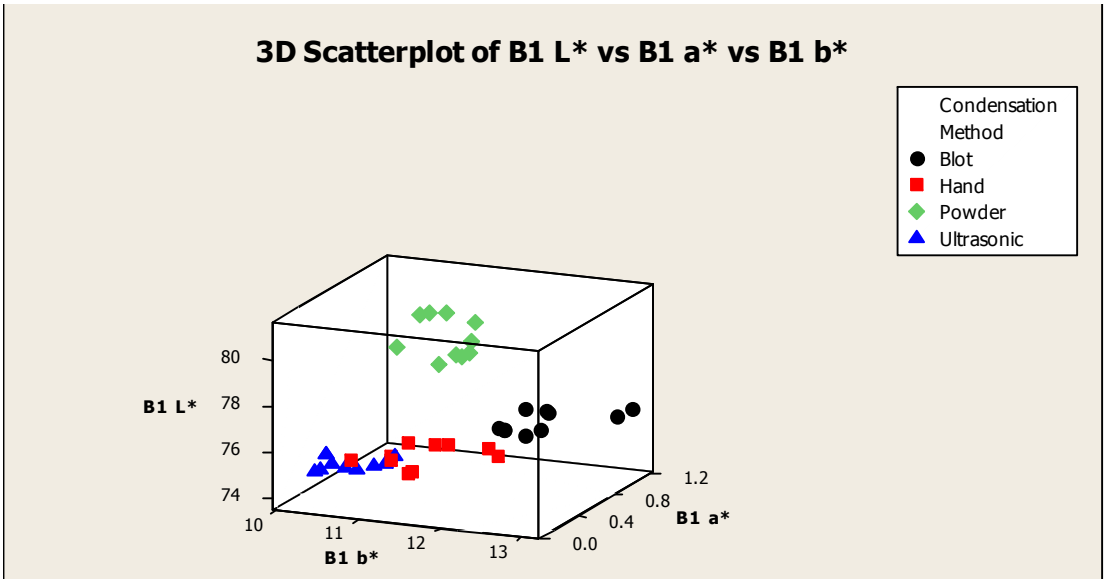


Table 40 Differences in ΔE_{00}, using Mean L*a*b* Co-ordinates, between Condensation Groups (Shade B1)

		ΔL*	Δa*	Δb*	ΔEoo
Blot v	Hand Vibration	-1.33	-0.28	-1.16	**1.27**
	Ultrasonic Vibration	-1.21	-0.56	-1.76	**1.62**
	Powder	3.71	-0.22	-0.94	**2.70**
Hand Vibration v	Ultrasonic Vibration	0.11	-0.28	-0.60	**0.55**
	Powder	5.04	0.06	0.22	**3.58**
Ultrasonic Vibration v	Powder	4.93	0.34	0.83	**3.56**

Figure 5.30. Effects of Condensation Technique on Mean L*a*b* Colour Co-ordinates (Shade A3)

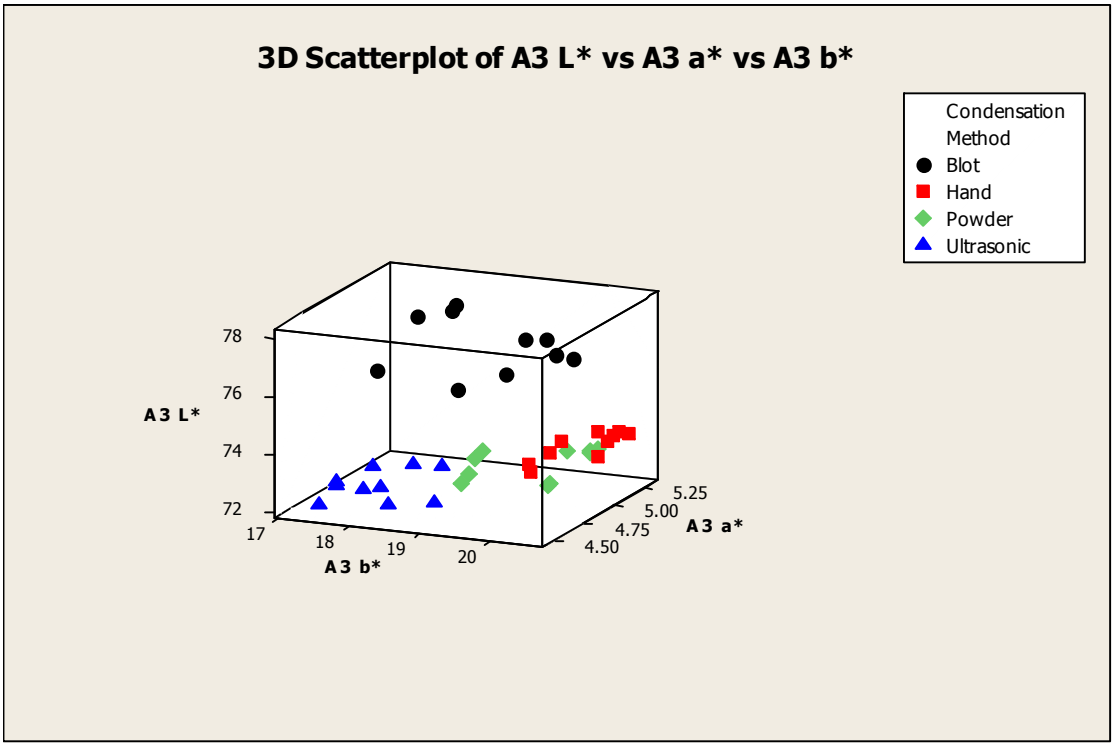


Table 41 Differences in ΔE_{00}, using Mean L*a*b* Co-ordinates, between Condensation Groups (Shade A3)

		ΔL*	Δa*	Δb*	ΔEoo
Blot v	Hand Vibration	-3.38	0.10	1.22	**2.55**
	Ultrasonic Vibration	-4.42	-0.27	-1.06	**3.29**
	Powder	-4.22	0.11	0.47	**3.09**
Hand Vibration v	Ultrasonic Vibration	-1.04	-0.38	-2.28	**1.46**
	Powder	-0.83	0.01	-0.74	**0.75**
Ultrasonic Vibration v	Powder	0.21	0.39	1.53	**0.87**

Figure 5.31. Effects of Condensation Technique on Mean L*a*b* Colour Co-ordinates (Shade D4)

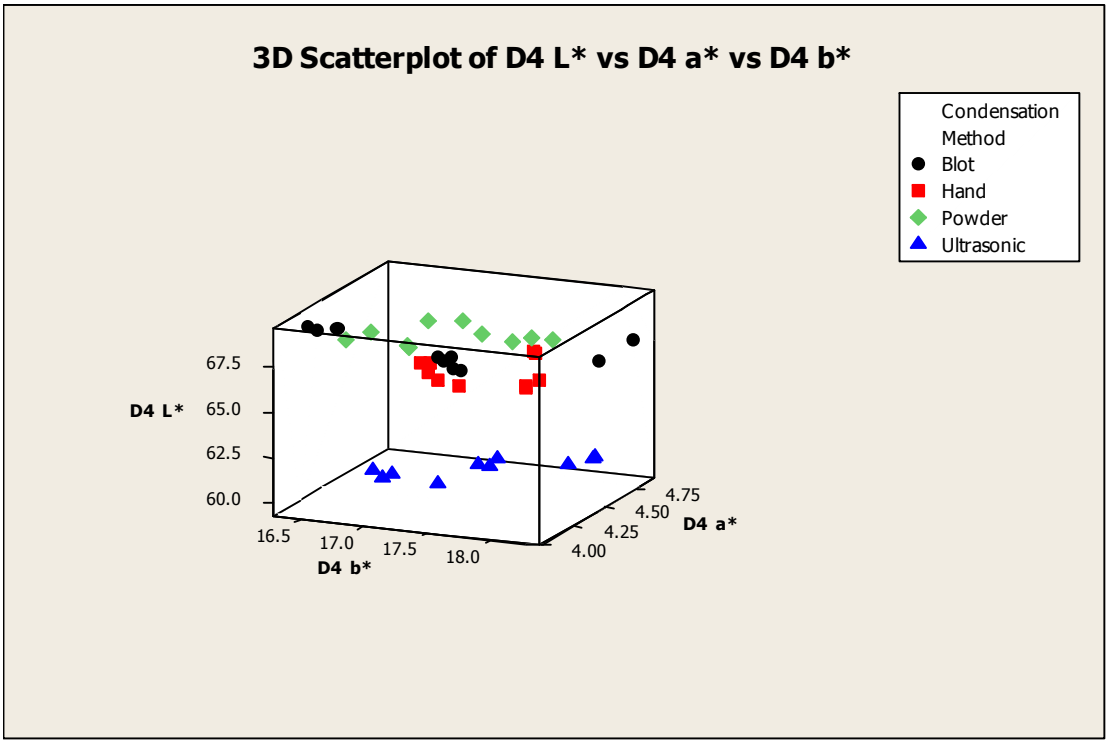


Table 42 Differences in ΔE_{00}, using Mean L*a*b* Co-ordinates, between Condensation Groups (Shade D4)

		ΔL*	Δa*	Δb*	ΔEoo
Blot v	Hand Vibration	-1.53	0.11	0.20	**1.24**
	Ultrasonic Vibration	-6.98	0.14	0.15	**5.82**
	Powder	0.83	0.01	0.05	**0.66**
Hand Vibration v	Ultrasonic Vibration	-5.45	0.03	-0.05	**4.59**
	Powder	2.36	-0.10	-0.15	**1.89**
Ultrasonic Vibration v	Powder	7.81	-0.13	-0.10	**6.47**

Table 43 ANOVA Statistical Comparison of the Mean L*a*b* Values from Different Condensation Groups (Shade B1)

				p-value
L*	Blot v	Hand Vibration		0.000
		Ultrasonic Vibration		0.000
		Powder		0.000
	Hand Vibration v	Ultrasonic Vibration		0.638
		Powder		0.000
	Ultrasonic Vibration v	Powder		0.000
a*	Blot v	Hand Vibration		0.009
		Ultrasonic Vibration		0.000
		Powder		0.014
	Hand Vibration v	Ultrasonic Vibration		0.001
		Powder		0.436
	Ultrasonic Vibration v	Powder		0.000
b*	Blot v	Hand Vibration		0.000
		Ultrasonic Vibration		0.000
		Powder		0.000
	Hand Vibration v	Ultrasonic Vibration		0.001
		Powder		0.137
	Ultrasonic Vibration v	Powder		0.000

Black = not statistically different (p>0.05), Red = significant difference (p<0.05)

Table 44 ANOVA Statistical Comparison of the Mean L*a*b* Values from Different Condensation Groups (Shade A3)

				p-value
L*	Blot v	Hand Vibration		0.000
		Ultrasonic Vibration		0.000
		Powder		0.000
	Hand Vibration v	Ultrasonic Vibration		0.000
		Powder		0.000
	Ultrasonic Vibration v	Powder		0.178
a*	Blot v	Hand Vibration		0.380
		Ultrasonic Vibration		0.011
		Powder		0.000
	Hand Vibration v	Ultrasonic Vibration		0.000
		Powder		0.887
	Ultrasonic Vibration v	Powder		0.000
b*	Blot v	Hand Vibration		0.000
		Ultrasonic Vibration		0.002
		Powder		0.150
	Hand Vibration v	Ultrasonic Vibration		0.000
		Powder		0.001
	Ultrasonic Vibration v	Powder		0.000

Black = not statistically different (p>0.05), Red = significant difference (p<0.05)

Table 45 ANOVA Statistical Comparison of the Mean L*a*b* Values from Different Condensation Groups (Shade D4)

				p-value
L*	Blot v	Hand Vibration		0.001
		Ultrasonic Vibration		0.000
		Powder		0.033
	Hand Vibration v	Ultrasonic Vibration		0.000
		Powder		0.000
	Ultrasonic Vibration v	Powder		0.000
a*	Blot v	Hand Vibration		0.146
		Ultrasonic Vibration		0.123
		Powder		0.950
	Hand Vibration v	Ultrasonic Vibration		0.644
		Powder		0.068
	Ultrasonic Vibration v	Powder		0.076
b*	Blot v	Hand Vibration		0.408
		Ultrasonic Vibration		0.588
		Powder		0.836
	Hand Vibration v	Ultrasonic Vibration		0.796
		Powder		0.411
	Ultrasonic Vibration v	Powder		0.662

Black = not statistically different ($p>0.05$), Red = significant difference ($p<0.05$)

The amount of condensation of the ceramic slurry should have varied with each group. The lightness (L*) also varied with these groups and with shade of ceramic. The group C (ultrasonic) tabs were almost exclusively the darkest and group A (blot dried) tabs were almost always lighter than both groups B (hand vibration) and C. The group D (addition of ceramic powder) samples were never found at the extremes of the lightness measurements. The maximum colour difference (ΔE_{00}) when varying the method of condensation was approximately 5, 4.5 and 8 units for shades B1, A3 and D4 respectively, all of which would be clinically perceptible.

The L* order, from highest to lowest, was:

i. Shade B1: Groups D, A, C and B with substantial overlap between groups B and C

ii. Shade A3: Groups A, B, D with C with overlapping of groups D and C

iii. Shade D4: Groups D, A, B and C, with overlap between group A tabs and both D and B

All group C tabs had the lowest L* values, except with shade B1. However, these B1 tabs had the second lowest mean value by only 0.11 units. This indicated that the ultrasonically condensed tabs were generally the darkest tabs as the remainder of the majority of the group C tabs had the lowest L* by at least one unit. For shades B1 and D4, the group D tabs were always the lightest whilst group A A3 tabs were darkest. With regard to lightness, statistical analysis (Tables 43 to 45) recorded that there were significant differences between all of the tab groups with 2 exceptions: the B1 group B and C tabs and the A3 group C and D tabs. The differences in lightness between almost every group would have been clinically visible.

The a* changed by less than L*. Although the effect was small (≤0.5 units), there was minimal cross over between groups of B1 and A3. Tables 43 to 45 recorded statistical differences in a* across the condensation groups of B1 and A3 with three exceptions: the group B and D of both B1 and A3 and A3 groups A and B. No statistically significant differences were found when the a* values of the D4 tabs were compared. The differences in a* values between almost every group would not have been clinically perceptible.

The b* co-ordinates (yellowness) were affected to a greater extent than the a* but not to the extent of L*. Shade D4 tabs had only a 0.15 Δb* unit change between the colour co-ordinates across the groups, compared to ≈2 units for the other shades. The b* values from each group had overlap with other groups for all shades, except

for shade B1 between the A and D groups. The order of b*, using the mean of the mean values, from highest to lowest were:

i. Shade B1: Groups A, D, B then C
ii. Shade A3: Groups B, D, A then C
iii. Shade D4: Groups B, C, D and A

For shades B1 and A3, group C tabs had the lowest b* values indicating ultrasonically condensed samples were the least yellow. Differences between the condensation groups were observed but no other trends were found, statistical analysis confirmed these differences with two exceptions (Table 43 to 45): group D and B (shade B1) and D and A (shade A3). All of the group A tabs of shade B1 were more yellow than the remaining tabs of this shade by <1 unit from the next tab group. The method of condensation did not statistically effect the b* of D4 tabs. For shades B1 and A3, it was hard to determine if the differences in b* would have been clinically relevant. The b* differences of D4 tabs would not have had a clinical impact.

5.6.1 The Fabrication and Spectrophotometric Consistency of Metal-Ceramic Samples Produced by Varying the Ceramic Condensation Method (Expt. 8)

It was found in previous experiments using Spectraflash that intra-set data variation was extremely small and this was repeated in this experiment.

Group A tabs produced colour differences (ΔE_{00}) between tabs in the same group that were significantly larger than the other tab groups ($p<0.001$). This was due to

the very simple but presumably variable method of removing water and condensing particles in the ceramic slurry via capillary action. This would lead to samples with larger variations in colour due to differences between the methods with regard to:

1. the degree of particle packing and spacing
2. the quantity of water removed
3. homogeneity, due to the amount of vibration

The shade of ceramic also influenced the reproducibility of the colour of ceramic. Shade D4 tabs had the highest mean colour difference values. There were statistical differences between the D4 and both the A3 and B1 tabs ($p<0.05$), however, no difference was found between the B1 and A3 tabs ($p>0.05$). This suggested that D4 Vita VMK 95 body ceramic was less reliable at producing tabs of the same colour than the other two shades tested. This was different from the inferences made about repeatability in the early experiments using shade guide tabs and IdentaColor II: these suggested B1 shade tabs were less reliably measured. These initial tests were, however, a comparison of the measurement repeatability as opposed to fabrication repeatability in this experiment. Experiment 4 established that the 2 mm shade B1 tabs had the largest colour differences and D4 tabs the smallest when considering fabrication repeatability. However, in both experiments 6 and 7, the D4 tabs had the largest variations in colour. The magnitudes of the differences in both these experiments was always below the acceptability threshold and often below the perceptibility threshold, but were statistically significant in some instances. The instrument drift found in experiment 6 was colour measurement inconsistency as opposed to a fabrication problem. The reason for the differences in colour reproduction between the shades was unknown, but it was likely that small variations in the ceramic powder particle size between the shades would have had

an influence: the degree of packing would vary with different particle sizes and therefore influenced the colour co-ordinates recorded.

In summary, B1 were generally the least reliably measured and possibly fabricated. However, certain aspects of sample fabrication (poorer ceramic slurry condensation, increased number of firing cycles) improved the reliability of B1 and worsened that of the other shades.

5.7 The Effects of Varying Ceramic Condensation on Porosity (Expt. 9)

The number of sub-surface pores on the sectioned surface of each tab was measured by the pointing counting method. The mean pore counts with their standard deviations were recorded in Table 46 and Figure 5.32 whilst the statistical analyses were recorded in Table 47.

Table 46 Mean (±SD) Sub-Surface Pore Counts for Tabs from Different Condensation Groups

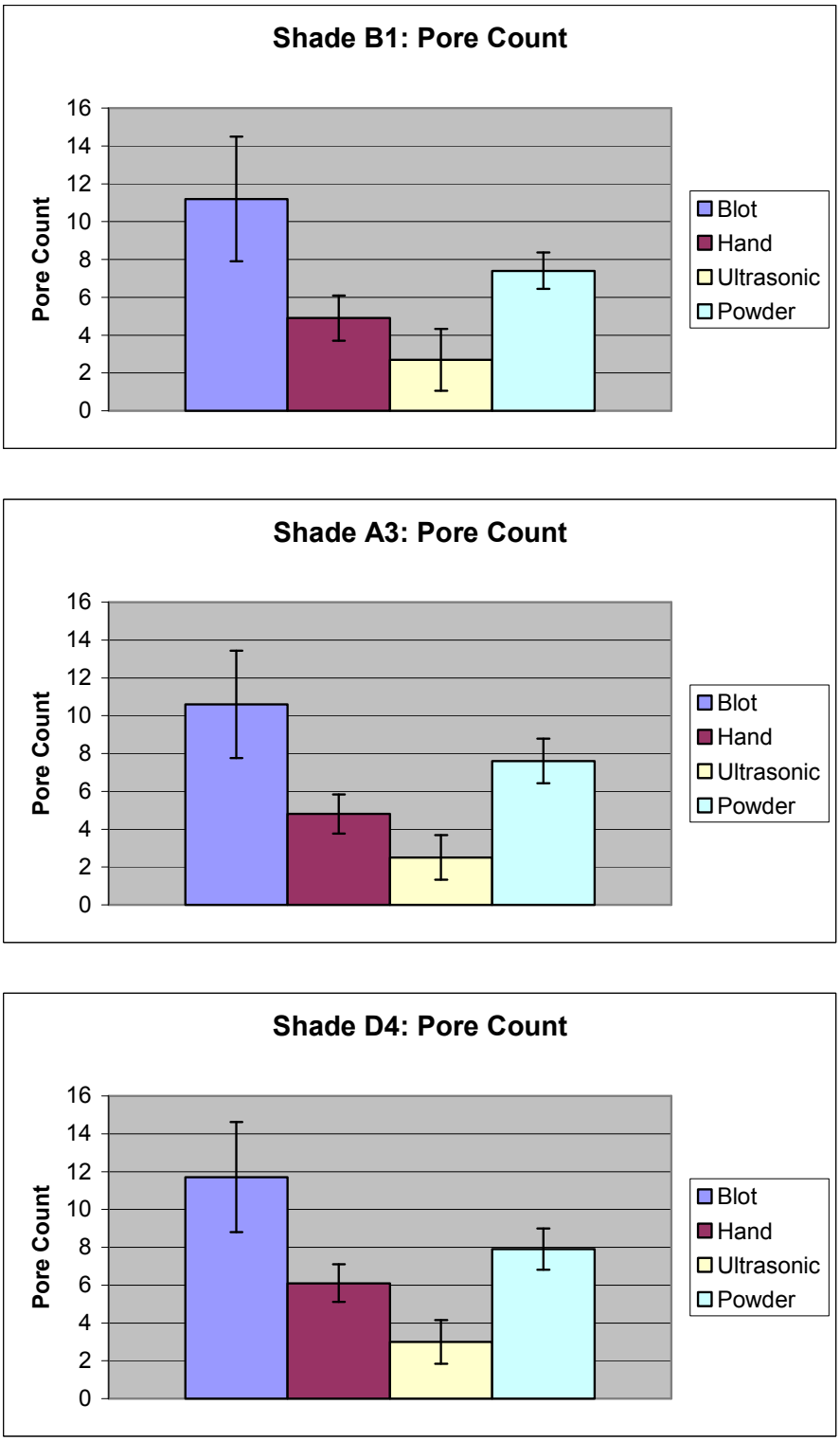
	Blot		Hand		Ultrasonic		Powder	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Shade B1	11.20	3.29	4.90	1.20	2.70	1.64	7.40	0.97
Shade A3	10.60	2.84	4.80	1.03	2.50	1.18	7.60	1.17
Shade D4	11.70	2.91	6.10	0.99	3.00	1.15	7.90	1.10

Table 47 Statistical Analysis of the Sub-Surface Pore Count for Tabs from Different Condensation Groups

		Shade B1		Shade A3		Shade D4	
		p-value	C.I.	p-value	C.I.	p-value	C.I.
Group A v B		0.000	-8.63,-3.97	0.000	-7.80,-3.80	0.000	-7.64,-3.56
Group A v C		0.000	-10.94,-6.06	0.000	-10.14,-6.06	0.000	-10.78,-6.62
Group A v D		0.003	-6.08,-1.52	0.006	-5.04,-0.96	0.001	-5.87,-1.73
Group B v C		0.003	-3.55,-0.85	0.000	-3.34,-1.26	0.000	-4.11,-2.09
Group B v D		0.000	1.48,3.52	0.000	1.48,3.52	0.001	0.82,2.79
Group C v D		0.000	3.44,5.96	0.000	4.00,6.21	0.000	3.84,5.96

Black = not statistically different (p>0.05), Red = significant difference (p<0.05)

Figure 5.32. Mean (±SD) Sub-Surface Pore Counts for Three Shades v Condensation Technique



In addition to the pore counts, the percentage of the surface classified as a pore, using an Image Analysis Technique (IAT) was calculated. The area occupied by pores beneath the site of colour measurement was calculated and recorded in Tables 48 and Figure 5.33. The statistical analyses were recorded in Table 49.

Table 48 Mean (±SD) Sub-Surface Porosity as a Percentage for Tabs from Different Condensation Groups

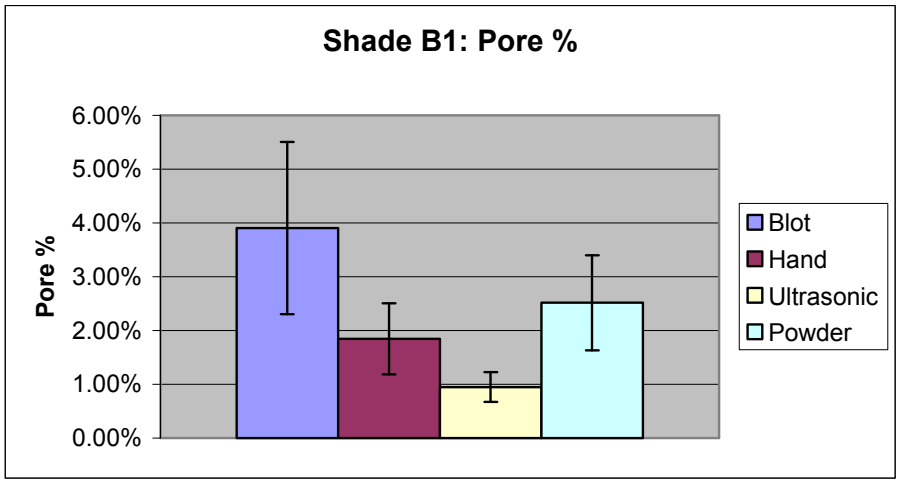
	Group A		Group B		Group C		Group D	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Shade B1	3.90%	1.60%	1.84%	0.66%	0.95%	0.27%	2.52%	0.88%
Shade A3	3.67%	1.66%	1.86%	0.83%	0.84%	0.24%	2.49%	0.87%
Shade D4	4.26%	1.65%	2.07%	0.58%	1.12%	0.22%	2.89%	0.83%

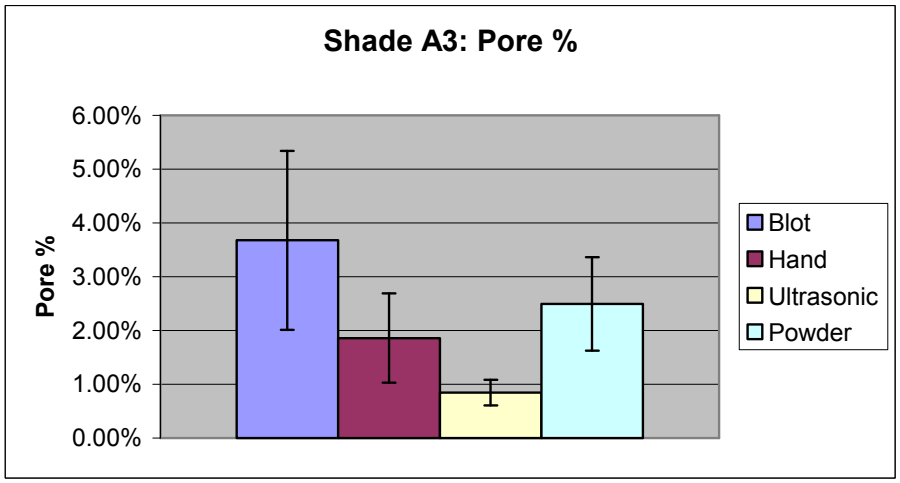
Table 49 Statistical Analysis of the Sub-Surface Porosity as a Percentage for Tabs from Different Condensation Groups

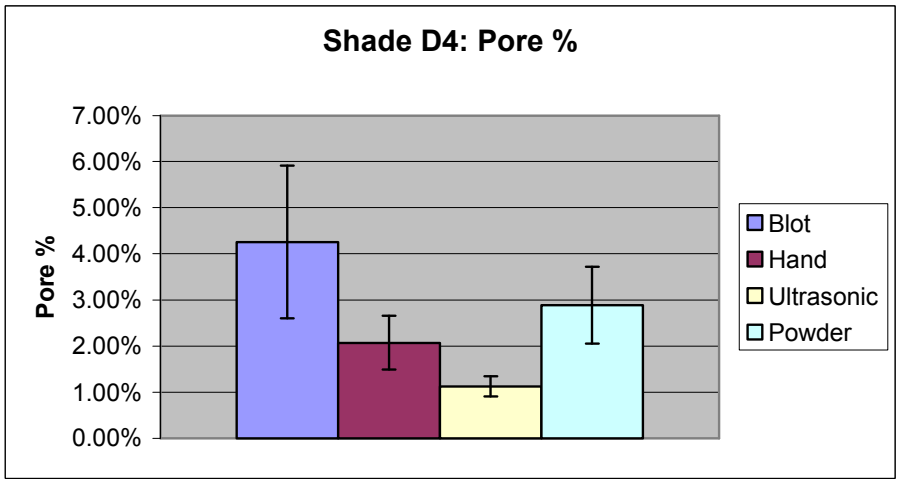
		Shade B1		Shade A3		Shade D4	
		p-value	C.I.	p-value	C.I.	p-value	C.I.
Group A v B		0.001	-3.21,-0.91	0.006	-3.05,-0.58	0.001	-3.35,-1.02
Group A v C		0.000	-4.03,-1.87	0.000	-3.94,-1.72	0.000	-4.24,-2.02
Group A v D		0.028	-2.60,-0.17	0.061	-2.43,0.06	0.031	-2.60,-0.14
Group B v C		0.001	-1.37,-0.42	0.002	-1.59,-0.44	0.000	-1.36,-0.54
Group B v D		0.069	-0.06,1.41	0.114	-0.17,1.42	0.021	0.13,1.49
Group C v D		0.000	0.96,2.19	0.000	1.05,2.24	0.000	1.19,2.33

1. Black = not statistically different (p>0.05), Red = significant difference (p<0.05)
2. Group A = Blot dried, B = Hand Vibration, C = Ultrasonic, D = Addition of Powder

Figure 5.33. Mean % (±SD) Sub-Surface Porosity for Three Shades v Condensation Technique







Statistical analysis revealed that shade had no effect on the porosity of a sample (either method of assessment) across all of the groups ($p>0.05$). However, samples of shade D4 consistently had the highest porosity for each group.

The porosity (pore counts and porosity percentage) for each group were different (A (blot), B (hand vibration), C (ultrasonic), and D (addition of powder). Group A tabs, of all shades tested, had a higher porosity than the other tab groups. The porosity of the tabs was given an order, from highest to lowest:

- Group A: Uncondensed (blot dried only)
- Group D: Addition of powder
- Group B: Hand vibration
- Group C: Ultrasonic vibration

For group A, the amount of water removed would be less than the other methods and also more unpredictable. In addition, the particle packing and spacing would be less predictable and this was reflected in the porosity values and SD's which were substantially smaller for groups B, C and D. A relationship between the porosity and the method of ceramic condensation was evident with no cross-over between group A and C tabs, regardless of the method of porosity assessment with one exception: the B1 tabs using the IAT.

Statistical differences ($p<0.05$) were found between all tab groups, of the same shade, for the pore counting method (Table 47). Table 49 recorded that statistical differences ($p<0.05$) were found between the porosity percentages of all tab groups and shades with three exceptions: shade A3 tabs from groups A and D ($p>0.05$), and tabs of both shades A3 ($p>0.05$) and B1 ($p>0.05$) from groups B and D. Group

D tabs which had large standard deviations were involved in both of these comparisons, this may have influenced the statistical findings.

Group A tabs were the most poorly condensed tabs and group C the best. It was concluded that the amount of condensation was related to the number of pores in a sectioned area of a specimen. Additionally, group B tabs were less porous and therefore more condensed than group D tabs.

5.8 Relationship between Colour Co-ordinates and Porosity

Regression analysis was used to examine the relationship between porosity and the L*, a* and b* colour co-ordinates. A summary of the linear regression analyses for both methods of porosity assessment was seen in Table 50 with the slopes of best fit shown in Table 51. The porosity levels used in the analysis were both pore counts and total porosity %.

Table 50 Expt 10: Summary of Linear Regression Analyses

Pore Count and L*a* b*									
	B1			A3			D4		
	L*	a*	b*	L*	a*	b*	L*	a*	b*
R-Sq	12.1%	37.3%	55.3%	51.7%	11.1%	4.4%	55.1%	12.4%	13.2%
Porosity % and L*a* b*									
	B1			A3			D4		
	L*	a*	b*	L*	a*	b*	L*	a*	b*
R-Sq	8.1%	32.5%	44.1%	42.8%	6.7%	5.3%	46.1%	17.7%	18.9%

Table 51 Expt 10: Slope of Linear Regression Graphs

	B1		A3		D4	
	Pore Count	**Porosity %**	**Pore Count**	**Porosity %**	**Pore Count**	**Porosity %**
L*	2.03	2.08	1.30	1.41	2.13	2.34
a*	0.25	0.22	0.21	0.25	0.16	0.16
b*	0.48	0.53	0.98	0.98	0.16	0.15

Red values indicated a negative correlation

The porosity increased as the value of each co-ordinate increased, the only exception to this were the a* and b* of the D4 tabs where the opposite was true. Regardless of the method of porosity measurement, the relationship between the slopes of the graphs for each shade and colour co-ordinates was similar. This verified the method as although porosity was assessed in different ways the results were similar.

The method of condensation affected the porosity and the colour co-ordinates. All three colour co-ordinates were affected but the magnitude and direction of shift was shade dependent:

a. Increased porosity correlated with an increased L*. The changes seen in the L* co-ordinates and porosity gave R-Sq≈50 for both methods of porosity

assessment for shades A3 and D4. However, for B1 the correlation was less (R-Sq≈10).

b. The changes in a* were very small with weak correlation (R-Sq≤37.3), however, the correlation was always positive. The strongest correlation was seen with shade B1.
c. A positive correlation existed between b* and porosity for shades B1 and A3. Increased porosity correlated with increased yellowness for shade B1 (R-Sq≈50) with a very weak correlation for shade A3 (R-Sq≈5). However, there was a weak, negative correlation for tabs of shade D4 (R-Sq≈15).

Shade D4 had the largest changes in L* and also the largest variations in pore count. These factors may be related as changes in pore number would influence L*.

CHAPTER 6: DISCUSSION

6.1 Colour Measuring Instruments

Shade measuring devices have potential advantages as they remove subjectivity when selecting the colour for a dental restoration. The literature review supported this whilst the ability to record quantitative data was a further theoretical advantage.

IdentaColor II (a microspectrometer) was selected for use in this study being representative of modern instruments designed for in-surgery and laboratory use. There were little data regarding its accuracy and consistency.

In later parts of the investigation measurements were made using a spectrophotometer. This was chosen in preference to a colorimeter as it was more discerning at detecting small colour differences (O'Neal et al 1987). There was little indication for employing human observers due to their inconsistency whilst instrumental colour differences do not correspond with those from human observers (Goldstein and Schmitt 1993, Yap et al 1999, Paul at al 2004 and Klemetti et al 2006).

6.2 Materials

Three types of samples were used (a) proprietary porcelain shade tabs, (b) custom all-ceramic samples and (c) custom metal-ceramic samples. The review of the literature revealed that sample type can affect the accuracy of a spectrophotometer's measurements (Seghi et al 1989a and Yap et al 1999).

The Vita VMK 95 porcelains for metal-ceramics were chosen as they were widely used in clinical practice. In addition, there was no evidence in the dental literature of their being extensively tested in this manner. The literature abounds with the effects of ceramic thickness on colour, but strangely there was little work which considered the possible interaction of thickness with method of construction.

6.3 Method

6.3.1 Mode of Preparation of Ceramic Samples

Proprietary shade tabs, custom all-ceramic and custom metal-ceramic tabs were used. The proprietary tabs represented a standard ceramic produced by heat and pressure in the manufacturer's factory. Both all-ceramic and metal-ceramic custom-made samples were examined as masking a metal substrate was thought to influence the colour of the porcelain.

Measurements were made at a consistent location on the samples to maintain consistency (Schwabacher and Goodkind 1990). Shades B1, A3 and D4 were selected as these corresponded to a high (shade B1), low (shade D4) and middle (shade A3) Value tab on the Vita Classical porcelain shade guide. The removal of surface staining and the glazed surface allowed their influence on the colour of the tabs to be eliminated.

The custom-made samples were polished rather than glazed: this provided a glaze-like finish without the introduction of a glaze firing cycle which had been shown to alter the colour co-ordinates (Brewer et al 1991 and Stavridakis et al 2004). The all-ceramic samples were made of pure dentine ceramic and the metal-ceramic samples consisted of opaceous and dentine: no enamel was used to reduce the

number of variables involved in construction of the samples. The thickness of both the opaceous layer and the dentine layer was important and was verified. The method used by Evans et al (1990) measured four points on each sample's surface. In this study a fifth measurement was made in the centre of each custom-made tab using digital callipers to verify the thickness. The silicone holder used to locate the samples during measurement could have exerted an influence on the colour, a reflecting agent was placed in the holder as recommended by O'Brien et al (1991a) to minimise this.

The Society of Dyers and Colourists (2002) stated that samples should be acclimatised before testing. It seemed unlikely that this requirement was important for dental porcelain, however, the samples were stored in the measuring room for 24 hours prior to testing as recommended.

6.3.2 Colour Measurement

IdentaColor II was operated via a touch-screen panel which allowed selection of the colour scale and sample type. The tip of the measuring probe was placed against the sample and light was transmitted through the tip. The shade selections, or colour values, were displayed almost immediately.

The spectrophotometer (Spectraflash SF600) was operated via the instrument control panel with the software programme linked to it to store the data. The illuminant (D_{65}) used by Spectraflash represented an average daytime source which was considered appropriate for this type of testing by the Society of Dyers and Colourists (2002). The Specular Content Inclusion (SCI) setting was used, meaning the specular port was closed to allow collection of all reflected light. This setting was

more accurate when measuring glazed dental samples (Lee et al 2002 and 2004). The larger C.I.E. field of view (10° standard observer) was used in these investigations.

The 1976 C.I.E. L*a*b* scale was used with ΔE_{00} formula despite their limitations: the latter having advantages over the ΔE_{ab} formula which was considered earlier in the literature review. However, the majority of results from other studies were derived from the older ΔE_{ab} formula which made comparison with other work more difficult.

6.3.2.1 Short-Term Repeatability of Spectrophotometers

The protocol used to assess the short-term repeatability of a spectrophotometer in measuring samples was formulated by the Society of Dyers and Colourists and the National Physical Laboratory Optical Radiation Measurement (N.P.L. O.R.M.) Club. In 2002, they recommended that thirty–one measurements were made of each sample, the literature did not provide any rationale for this. The first reading was discarded and the mean of the remaining thirty calculated. The colour differences, using the C.I.E.DE 2000 colour difference equation, between the mean colour co-ordinates and each of the remaining thirty individual readings were calculated (Δe). Within the results from experiments 1 to 3 using IdentaColor II, the discarded measurement was noticeably higher or lower than the mean of the samples, thus supporting the protocol. For example, the first reading in experiment 2 (dental surgery lighting) had a lower L* value by almost 3 units compared to the mean (Appendix S). The reason for this was not apparent but IdentaColor II may require a

period of warming up before use. This time may make it impractical in a dental surgery.

There were differences observed between measurements of the same sample on different days. The literature revealed that operator variation can account for 0.34 ΔE_{ab} units (Douglas and Brewer 1998) and device/positioning variation accounted for 0.48 ΔE_{ab} units (Paul et al 2002).

6.3.2.2 Thresholds for Repeatability Tests

The literature indicated that two different repeatability thresholds were appropriate for *in vivo* and *in vitro* studies. Thresholds were lower for *in vitro* testing as variables were more easily controlled. The threshold for perceptibility was 0.4 colour difference (ΔE_{00}) units and this was regarded as the lowest possible level of detection of any material under ideal viewing conditions by trained observers.

The threshold of acceptability for this investigation was set higher at 1 ΔE_{00} unit, chosen from the work of Ragain and Johnston (2000). It represented the point at which 50% of their observers identified a difference between 50% of the samples. In this study if the colour difference were greater than one unit, the reason was identified.

6.3.2.3 Coefficient of Variation

The coefficient of variation is dimensionless, allowing comparisons between populations that have different mean values and is reported as a percentage (%).

Jarad (2001) stated that the coefficient of variation should ideally be less than 5% for repeated measurements using digital photographic images. For the colour measurements of both IdentaColor II and Spectraflash the coefficient of variation in each data set was calculated. If it were greater than 1% for any of the individual colour co-ordinates (1976 C.I.E L*, a* or b*) then the method described by the Society of Dyers and Colourists was used to calculate colour differences. However, if the coefficient of variation were less than 1%, no further calculations were made.

6.3.3 Assessment of Ceramic Porosity

Two different methods of porosity assessment were used: the point counting method and an Image Analysis Technique (I.A.T.). Both were used as they assessed porosity in different ways, thereby reducing any intrinsic errors of each method. In addition, the point counting method only assessed a small area of each sample, whereas an I.A.T. allowed the whole of each sample to be assessed. The area assessed by the point counting method could have been increased by increasing the number of gridlines, however, the number of intersections used were felt to be sufficient to be representative of the tab.

6.3.3.1 Point Counting Method

The method was based on the protocol of Geirsson et al (2004). It involved subjective decision-making, however, the Cohen's Kappa scores between days 1 and 2 in the pilot studies were supportive of the technique. Each pixel was converted to black if its Red-Green-Blue value was <50 and white if >50.

Magnification of each intersection followed allowing easier identification of pores in the ceramic at an intersection.

6.3.3.2 Image Analysis Technique

The digital images were analysed using software to calculate the total area of porosity in each sample using the protocol from Guazzato et al (2004). After the images had been cropped following a strict protocol, no subjectivity could have influenced the results and therefore the images were analysed only once.

6.4 Results

The variability of the sample preparation influenced the colour co-ordinates recorded. In addition, sample presentation would have influenced the colour co-ordinates recorded, however, these effects should have be standardised for each sample type. Wang et al (2005) found that the co-ordinates recorded differed when different spectrophotometers and measuring modes were used: differences in values between authors and perhaps made comparisons less important. Definitive conclusions from comparisons to the literature were therefore more difficult. Bolt et al (1994) found that edge-losses varied between viewing window size but were consistent for each window size and therefore they should not have affected the results of this study or the other studies.

6.4.1 Expts. 1 to 3: Microspectrometer (IdentaColor II) Measurement of Porcelain Tabs

As discussed previously, the colour co-ordinates used by IdentaColor II were not representative of any C.I.E. L*, a* and b* co-ordinates, so for the sake of clarity they were renamed α, β and γ colour values. IdentaColor II's scale had a larger range and each co-ordinate was generally was larger than the values from the C.I.E. scale; the scales appeared to be related, but in an unknown way. The manufacturer was contacted, and apart from confirming that IdentaColor II did not use a C.I.E. or another recognised scale, little further information was provided. Therefore only tentative inferences regarding α, β and γ values could be drawn: increasing α values were thought to relate to increased lightness. An increase in β, above 0 was thought to indicate a red sample while values below 0 represented green samples. γ values indicated the amount of yellowness, higher values suggested more yellow samples. The ∆E (the colour difference between the mean of 2 data sets from IdentaColor II) was calculated using the α, β and γ values and the C.I.E.DE 2000 colour difference equation. These differences were not truly relevant as the co-ordinates were not from the 1976 C.I.E. L*a*b* colour space, but contributed to the discussion.

6.4.1.1 Effect of Re-calibration using IdentaColor II (Expt. 1)

The manufacturers advised re-calibration of their colour measuring device on request by the instrument, but no evidence was available to support this. Following this experiment, it was concluded that it was satisfactory to measure shade tabs, regardless of surface type, until the device requested calibration. This was normal procedure in colour measurement (Cheung et al 2002), followed the manufacturer's instructions for this device and was also the method recommended by The Society of Dyers and Colourists (2002).

6.4.1.2 Effect of Lighting using IdentaColor II (Expt. 2)

There was no evidence of an intra-oral spectrophotometer being tested in the literature under different ambient lighting conditions, therefore no comparisons were possible. Although it was recognised that the light source of the device was probably more important than the ambient lighting.

6.4.1.3 Repeatability of measurements with IdentaColor II

The repeatability of the measurements of the unaltered and ground proprietary tabs had never been assessed in the literature. However, the literature (Yap et al 1999) stated that curved surfaces were considered more difficult to measure than flat ones. However, no statistical differences were found between the Δe values from the different surfaces in experiments 1, 2 and 3A refuting this suggestion.

6.4.1.4 Reproducibility of measurements with IdentaColor II

Table 1 demonstrated there was considerable variability in the repeatability of devices. In a recent study, Khurana et al (2007), tested three spectrophotometers and found that agreement to be as low as 50% when considering these devices' selection of tooth shade in vivo, however each of the devices were repeated measurements were not discussed. The repeatability in this study was approaching 100% and therefore was at the more favourable end of the repeatability scale found in the literature, however as this is an *in vitro* study it would be expected that an increase in reproducibility would be present compared to *in vivo* studies.

6.4.1.5 Accuracy of measurements with IdentaColor II

Dozic et al (2007) is the only study in the literature to have used IdentaColor II. They analysed the accuracy of IdentaColor II by converting its shade selections into L*a*b* co-ordinates from a historical study. This can be considered as inappropriate due to the variability of the colour of shade guides discussed previously, however the results indicated that IdentaColor II was the least accurate.

For unaltered tabs, inaccuracy could be attributed to a combination of the surface colour changes associated with shade guide tabs (Sorenson and Torres 1987, Schwabacher and Goodkind 1990 and O'Brien et al 1991a). Ground tabs did not match the shade selection either which may be a result of removing the staining required to make the shade tab the desired shade. Incorrect calibration of the device may have accounted for this or the device was not intended to measure shade tabs (only metal-ceramic restorations or teeth). The shades selected differed in Value as well as Hue/Chroma, making comparisons between the selections difficult.

Shade Selections using IdentaColor II

IdentaColor II again did not record that any tab matched its intended shade. Using the Value order of Paravina et al (2001), the B1 and A3 metal-ceramic samples (expt. 3C) became darker as thickness increased but D4 remained approximately the same. IdentaColor II predominately selected 'A' shades (Tables 11 and 12) regardless of shade designation or tab surface. It was unknown if this device had incorrect calibration, was programmed to preferentially select 'A' shades or if the area measured on the tabs were not the intended colour (due to fabrication variables from Vita and the investigator). The shade selected for D4 was C3.5 which

was a substantial visual discrepancy (Paravina et al 2001). Unfortunately, another IdentaColor II device was not available to assess if the accuracy of the device tested was incorrect or if a systematic error was present. Dozic et al (2007) indicated that IdentaColor II had the poorest accuracy of the five shade-matching devices that they tested, making it more likely that a systematic error was present.

6.4.2 The Effects of Type and Thickness of Tabs on Spectrophotometric Measurements using Spectraflash SF600 (Expt. 4)

The results of this experiment supported those of Douglas and Przybylska (1999). The results indicated that a thicker layer of veneering ceramic reduced the colour difference between samples and a proprietary shade tab. In addition, both this investigation and Douglas and Przybylska (1999) found the shade tabs had smaller L*, a* and b* values.

Proprietary Shade Tabs (Expt. 4A)

The differences in colour co-ordinates found in Experiment 4A between the shades tested generally agreed with the available literature (Paravina et al 2001, Li 2003 and O'Brien et al 1991) relating to the L* values and the overall colour (a* and b*)

Kim et al (2003) found that an unpolished ceramic surface was darker than the polished surface by upwards of 2 L* units. The ground porcelain shade guide tabs were similar in surface finish to the unpolished ceramic, although the sample type was different. The results from both IdentaColor II and Spectraflash confirmed Kim et al's findings. The magnitudes of the changes similar, as Spectraflash showed

differences of >1.5 L* units depending on the shade tested. The IdentaColor II results could not be compared as different colour scales were used.

Custom All-Ceramic Samples (Expt. 4B)

Generally, these tabs became darker (smaller L*) as the thickness of ceramic increased, especially when the ceramic thicknesses were higher. This agreed with published studies (Jacobs et al 1987 and Terada et al 1989a) but not with the findings of Jorgensen and Goodkind (1979).

The red-green values (a*) appeared to be relatively consistent across the shades, although statistically significantly differences were found between tab thicknesses. The small increases in a* seen with increasing ceramic thickness for A3 tabs agreed with Jorgensen and Goodkind's (1979) findings.

The B1 and A3 tabs generally became less yellow (smaller b*) as ceramic thickness increased. This agreed with Brewer et al (1991) but conflicted with other literature (Jacobs et al 1987, Terada 1989a and Dozic et al 2003).

Custom Metal-Ceramic Samples (Expt. 4C)

The results of experiment 4C were supported by the literature (Nakamura et al 2002 and Douglas and Przybylska 1999). Nakamura et al's results were in complete agreement with all three aspects of colour (L*, a* and b*) when their 1 and 2 mm samples were compared to these results. Douglas and Przybylska's results were extrapolated and their data again agreed with regard to the lightness and redness (L* and a*), however the yellowness (b*) data could not be retrieved. The literature

review showed that 1.5 to 2 mm thickness of ceramic was needed to mask the underlying opaque ceramic and metal. The results of experiment 4C supported this, indicating that the 'true' colour of the ceramic had not been reached with the 1.5 mm samples. Figure 6.2 recorded that the colour of the 2mm custom-made samples were closer to the colour of the proprietary shade tabs than the other thicknesses of tab.

6.4.2.1 Repeatability of measurements with Spectraflash SF600

Table 1 and Figure 2.4 demonstrated variability in the literature with regard to the repeatability of colour-measuring devices at recording the colour co-ordinates, and therefore shade, of samples. These studies did not always use the same type of device, test sample, shade or the same method for assessing repeatability which may have contributed to this variability. These studies provided mean colour co-ordinates from 2 measurements (Keuhni and Marcus 1979), 3 measurements (Johnston and Kao 1989 and Lee and Powers 2005b) or 10 measurements (Seghi et al 1989b). Sometimes the samples were measured only once (Ruyter 1987 and Ragain and Johnston 2000) or the number of measurements was not clear (O'Brien et al 1991b). In addition, other commonly quoted studies showed variability: mean of 3 measurements (Ecker and Moser 1987, Goldstein and Schmitt 1993, Okubo et al 1998, Paravina et al 2001, Paravina 2002, Paravina et al 2002, Dozic et al 2003, Wang et al 2005), 3 to 5 automatic measurements (Tung et al 2002), 5 (Vichi et al 2000) or 10 measurements (Douglas 1997). Sometimes the samples were measured only once (Paul et al 2002 and Wee et al 2002) or the number of measurements was not clear (Lee et al 2004, Paul et al 2004). None of these studies gave an indication of the variation between the measurements.

Several studies discussed the differences between measurements of the same samples. Goldstein and Schmitt (1993) found colour differences of (0.57 to 2.75 ΔE_{ab} units) when ceramic was measured on two occasions. The results of the study from Ishikawa-Nagai et al (1994) results were smaller (0.22±0.13 ΔE_{ab} units) whilst King and deRijk's study (2007) found a range of differences, but the maximum was 0.69 ΔE_{00} units. The results across the shades from experiments 4B and 4C were 0.39 ± 0.23 (Table 22) and 0.35 ± 0.19 (Table 27) respectively. The results of experiment 4 showed good consistency over time when compared to other reported work.

6.4.3 The Effects of Metal Treatment and Opaque Ceramic on Spectrophotometric Measurements (Expt.5)

De-gassing the metal backings caused them to become substantially darker and slightly more yellow. The addition of the wash opaque caused a major increase in the L*, a* and b* values of the tabs. These results were in agreement with Brewer et al (1991) with the exception of the direction of the b* change following de-gassing and the a* change after the application of opaque ceramic.

Shade-designated opaque ceramic made the tabs lighter, redder and less yellow compared to the colour of the tabs following the addition of dentine ceramic. This confirmed the findings of O'Brien et al (1991b) that opaque ceramics were lighter than samples containing both opaque and body ceramic and agreed with the work of Brewer et al (1991) using shade A2 ceramic with regard to lightness and yellowness.

The previous experiments showed that thickness and sample type affected the colour and to a lesser extent repeatability of measurements: repeatability was better for metal-ceramic than all-ceramic samples. The opaque ceramic layer within the metal-ceramic samples and the slight differences in colour of the different increments within the all-ceramic samples would have accounted for this difference.

6.4.4 The Effects of the Number of Ceramic Firings on Spectrophotometric Measurements (Expt. 6)

In the literature, the effect of repeated furnace firings on the colour of dental ceramic was contradictory. The influence of firings on the colour of fired porcelain was examined using the custom metal-ceramic tabs in experiment 6. O'Brien et al (1991b) found differences of <2 ΔE_{ab} units between samples fired 3 and 6 times, but the size of the colour difference was dependent on the ceramic manufacturer. The results of experiment 6 agreed with O'Brien et al's study as small colour differences were found for Vita A3 ceramic. These differences may not have been clinically perceptible, but may contribute to colour mismatches. A recent study (Celik et al 2008) tested tabs of shades A1 and A3 and subjected them to repeated firing cycles. When compared to this investigation, they also found that lightness (L*) increased and redness (a*) decreased as the number of firings increased. However, the yellowness (b*) trends varied between these two investigations. Celik et al (2008) used all-ceramic samples, compared to the metal-ceramic samples used in experiment 6, which may have influenced the findings.

6.4.5 The Effects of Operator on the Spectrophotometric Measurements

There was surprising little evidence in the literature describing differences in colour of ceramic produced by different technicians, although it seems to be a common observation.

A range of colour differences (3.5 to 11.1 ΔE_{ab} units) were found when five different laboratories fabricated metal-ceramic crowns to match a shade tab that was provided (Douglas and Brewer 2003). The tabs produced during this investigation had substantially smaller colour differences than these, although a direct comparison was unfair as the operators in the Douglas and Brewer study had more variables such as ceramic batch, manufacturer variation, different furnaces and firing settings. Clinically, the differences in this investigation, between the operators would probably have been visible.

6.4.6 Effects of Varying Condensation Method (Expts. 8 and 9)

Effect on Colour

The evidence in the literature was contradictory: Evans et al (1990) found no difference in lightness but differences in redness/yellowness when the condensation method varied. They found the tabs to be redder and less yellow for uncondensed Vita VMK 68 ceramic when compared to conventionally prepared samples. However, Rosenstiel and Johnston (1988) found differences in lightness when the samples were over- or under- condensed. Under-condensed samples, which equated to Group A tabs samples in this investigation, were darker (by 0.7 units)

than the conventionally prepared samples. They also found lower yellowness levels (0.8 units), matching Evans et al's (1990) results. The results of experiment 8 found the severely under-condensed (Group A) samples to be a different colour than the conventionally prepared samples (Group B – hand vibrated). The colour differences were 1.27, 2.55 and 1.24 for shades B1, A3 and D4 respectively. For A3 (Table 41), the under-condensed samples were darker by 3.4 units, less yellow by 1.16 units and slightly less red (0.28 units) than the 'conventional' tabs.

Effect on Porosity

Zhang et al (2004) found that changes in total porosity were dependent on the powder/liquid ratio of the ceramic slurry. However, Evans et al (1990) stated there was no difference in the specific gravity of their samples fabricated using different methods of ceramic condensation. These two studies used different methods to assess porosity compared to each other and this investigation.

Zhang et al (2004) found that their most densely packed samples were less porous than the samples prepared conventionally. The results from experiment 9 support these findings, indicating that the most condensed samples were less porous and visa versa. Interestingly, Zhang et al's samples with the lowest powder:liquid ratio had the lowest porosity. This was explained by stating that the lower ratio allowed free movement of ceramic particles which resulted in lower porosity. However, the samples were prepared in a fundamentally different way to those of experiment 9. Zhang et al added a specific amount of water to a known weight of porcelain powder and then fired the slurry. In experiment 9, the slurries initially had the same powder:liquid ratio and then varying amounts of water was removed and the

remaining particles condensed prior to firing. This may have accounted for the differences between Zhang et al's finding and those of this investigation.

It was concluded that shade had a statistically insignificant influence on the porosity, although the results indicated that the D4 samples had a higher porosity. However, Jones and Wilson (1975) found differences in porosity between shades of B1 and C2.

6.4.7 Relationship between Spectrophotometric Measurements and Porosity

Differences in sub-surface porosity influenced the colour. Evans et al (1990) explained this by the inhomogeneous distribution of metal oxide pigments, accumulation of larger particles towards the metal-ceramic interface, loss of the finer and less pigmented ceramic particles with the removal of water as well as areas of particle agglomeration which resulted in different densities and different reflective properties. The direction of the colour change was shade dependent. Several reasons for these differences were postulated. The particles of different shades may be slightly different densities, sizes and weights, therefore a variable effect on the L*a*b* values across the shades, but from the same condensation group, were expected. Jones and Wilson (1975) found that A1 ceramic powders had smaller particles and subsequently a lower viscosity. This increased the number of pores compared to other shades.

For these reasons, it cannot be assumed that porosity was uniform throughout the ceramic samples or even that the plane of section used was representative of the remainder of the sample. The conclusions regarding colour and porosity therefore only related to the plane and section of the samples assessed. These two factors

may account for some of the variability seen in the results and different strengths of correlation of tabs from the same condensation group. The reasons for pore formation were described by Evans et al (1990) and Cheung and Darvell (2002): trapped gases in the matrix do not dissolve out, the gases produced via chemical reactions during sintering were trapped and air entrapment in the pre-sintered slurry.

The porosity measured in the sub-surface zone, where the colour was measured, influenced the scattering and absorption of light. As the number of pores increased, the a* and b* changed. In addition, as porosity increased L* increased. If a ceramic were less dense due to more porosity then fewer ceramic particles would have been present. This resulted in less light absorption and therefore a higher L*. Rayleigh scattering also contributed to the changes in L* values. Some particles within sintered ceramic were smaller than the incident light, so this would have occurred. More light therefore was lost to Rayleigh scattering in the more condensed samples, as there were more particles, making the tabs darker. Alternatively, more light may have been reflected back to the device by the pores than the ceramic itself, making porous samples appear lighter, although this seemed less likely.

6.4.8 Tab Fabrication

The investigator's samples were more consistent than the ceramists, however the ceramist's samples were closer to the colour of shade tabs. The conclusions made in this investigation were likely to be accurate although the magnitude of the differences may not be absolutely correct.

No literature was able to confirm the inference that certain modes of fabrication caused variability in the colour of samples. This is the first study to allow the

comparison of the colour between tabs from the same sample group and, in addition, related these findings to the porosity of the samples. For example, very poorly condensed tabs (expt. 8) showed poorer repeatability with regard to the colour differences between them when compared to other condensation groups. Condensation packed the ceramic powder particles closer together and it was assumed that each method removed a different amount of water and air. The location of the water remaining may have varied and powder particles would not have been as closely packed if less condensation occurred. This would have left pores of different sizes, at different depths, in each sample group which may have contributed to the intra-group and inter-shade differences in porosity. Porosity was assessed in a small area of the tabs directly below where the colour was measured. However, the influence of porosity on the surface or other areas in the sample was unknown.

6.5 Clinical Implications

There were some clinical implications following testing of IdentaColor II:

a) It was easy to use *in vitro* and it seemed likely this would be the case *in vivo*.
b) Clinical lighting will not adversely affect the shade selections.
c) The first shade measurement should probably be ignored. IdentaColor II does not have such instructions, but it seems advisable to allow some time for the device to warm-up.
d) Small changes in colour values were unlikely to have a significant clinical influence. For example, the colour value changes observed when the method of calibration was changed would not have altered the shade selected.

e) IdentaColor II tended to select lighter shades. If the shade selection was incorrect the shade of the restoration could be altered by the laboratory without remaking the restoration. The effect of this device preference for 'A' shades was difficult to assess without a clinical trial.

The influence of thickness on the colour of both custom-made all-ceramic and metal-ceramic samples was established for this ceramic. The clinical relevance of the changes in all-ceramic samples can be questioned as the ceramic tested was intended for use with metal-ceramic restorations. The yellowness of metal-ceramic samples was due to the opaque ceramics and dentine ceramics try to diminish these effects. The thickest (2 mm) metal-ceramic samples were closer to colour of the shade tab. This implied that the colour of metal-ceramic restorations became more "correct" as the thickness of ceramic increased (>1.5mm). This indicated the amount of tooth reduction required to achieve a colour match for a metal-ceramic restoration.

This implied that colour measurement of dental samples can be improved by having an opaque backing and measurement of all-ceramic samples may be more troublesome. This problem is also encountered clinically: the colour of all-ceramic restorations can be influenced by the colour of the underlying tooth substance and cement used making shade matching more difficult. Metal-ceramic restorations obviously do not have this problem but are generally considered less aesthetic.

The coping material, ceramic thickness, numbers of firings, operator and method of ceramic slurry condensation all affected the colour co-ordinates of the ceramic samples. The colour differences were usually large enough to have a clinical impact and therefore the mode of fabrication will influence the colour of restorations. A

consistent mode of fabrication should be employed by the dental technician to ensure that a restoration has the best chance of matching its intended shade. This is essential as the results found a visible colour difference between the two operators used in this investigation.

The literature has plentiful data to demonstrate that porosity affects the physical properties of ceramic. This data indicated that the colour of the ceramic was also influenced by porosity.

6.6 Further Work

Further investigations are needed before IdentaColor II can be fully recommended for clinical and laboratory use. Scant *in vivo* evidence of its efficacy and the discrepancy found in this investigation between the shade designation of the samples and the shade selected by IdentaColor II, indicated that further testing is required. Both lab tests to verify the calibration of the device and clinical tests to test the selection of restoration shades compared to human observers and other devices are required.

It cannot be stated with absolute certainty that a certain size of colour difference would be clinically visible. Therefore, the clinical relevance of the findings of this investigation also requires verification. A substantial investigation using the methods employed here and many human observers to correlate the colour differences is needed. A recent in vivo study found acceptability and perceptibility thresholds of 5.5 and 2.6 ΔE_{ab} units (Douglas et al 2007) which were substantially higher than the values used in this laboratory study (0.4 and 1 ΔE_{00} units respectively) which were

based on several previous studies. This demonstrates the large variability in the literature and therefore the need for further investigations.

Some of the experiments had a small sample size: this occasionally made statistical analysis less powerful (for example, firing cycle experiment). However, some aspects of this investigation require further investigation:

Expt. 2. There may have been shade-dependent differences when assessing repeatability under different lighting conditions and therefore all shades and different shade guides should be investigated.

Expt. 3. Shade B1 tabs under different lighting conditions and ground tabs were not as repeatable over time. This may require further investigation. The shade calibration of this device needs investigation as the shade selection did not match the expected shade. In addition, a 50:50 mixing ratio of A2:A3 ceramic would not have produced A2.5, making these types of shade selection not useful, as this shade guide does not arrange its tabs in a uniform fashion (Miller 1987).

Expts. 6. & 8 The effect of shade on the consistency of fabrication requires further investigation. If differences between shades are confirmed this would have clinical implications.

Investigation of the influence of other ceramic variables such as ceramic manufacturer, metal or non-metal coping and types of ceramic (or other aesthetic materials) is needed. In addition, different colour measuring devices (shade taking devices) and shades of ceramic should be investigated.

CHAPTER 7: CONCLUSIONS

Within the limitations of this study, the following conclusions were drawn:

Regarding mode of fabrication and colour measurement:

1. The colour scales used by IdentaColor II and Spectraflash SF 600 were different.
2. The recorded colour co-ordinates (values) and shade of the ground proprietary tabs were different compared with the unaltered ones: these differences were sufficient to be recognised by the eye.
3. IdentaColor II was easy to use in vitro and should be transferable to the intra-oral environment. However, its accuracy must be verified. Spectraflash SF600 could not be used intra-orally.

For IdentaColor II specifically:

1. The results were repeatable both within a data set and over time.
2. Its accuracy could not be evidenced as it did not use a C.I.E. scale.
3. Colour values varied slightly with changes in the calibration method, lighting and time.
4. Proprietary shade guide tabs and custom-made all-ceramic tabs of the same shade were not the same colour.
5. The thicker all-ceramic tabs of shades B1 and A3 were closer to the shade of the unaltered proprietary tab.
6. The shade selected by IdentaColor II did not match the shade designation of the samples.

For Spectraflash SF600 specifically:

1. The data sets were consistent both within each set and over time.
2. The results were more consistent than those of IdentaColor II.

3. Increasing the ceramic thickness of both all- and metal-ceramic samples altered the L*a*b* co-ordinates recorded.
4. All co-ordinates decreased with increased thickness, however, the changes in lightness (L*) and yellowness (b*) were substantially greater than those for redness (a*).
5. For all-ceramic tabs, the L* changes correlated reasonably for B1 and A3 (R-Sq>68) but was better for b* (R-Sq>77).
6. For metal-ceramic tabs:
    a. L* changes correlated well with D4 and A3 and a* showed good correlation (R-Sq>80) for all shades whilst the correlation for b* was less.
    b. The thicker tabs tended to be closer to the colour of the proprietary tabs.
7. Lightness (L*) was more affected than the a* and b* co-ordinates by the mode of sample preparation (operator, firing cycles, condensation). The yellowness (b*) tended to be more affected than the a* (red-green) co-ordinates.
8. The mode of fabrication also affected the consistency of their colour values.

Conclusions regarding mode of fabrication, colour and porosity:

1. The method of condensation altered porosity and the L*a*b* co-ordinates.
2. Significant differences in L*, a*, b* and porosity were found for all shades between almost every different condensation group ($p<0.05$) with the exception of the a* and b* co-ordinates from D4.
3. The direction and magnitude of the changes in colour with different methods of condensation were often shade dependent.
4. Both methods of porosity assessment produced results with similar trends.

5. The removal of more water from the ceramic slurry resulted in less porosity.
6. A weak correlation existed between porosity and changes in colour when the condensation method was varied. The correlation R-Sq was ≤50 for all the L*, a* and b* co-ordinates.

The null hypotheses were therefore rejected:

1. There was no difference between the measurements of colour co-ordinates of dental ceramic made with two different colour measuring devices (IdentaColor II and Spectraflash SF600)
2. Variation in the mode of fabrication of porcelain samples will have no effect on the colour co-ordinates of ceramic or porosity

CHAPTER 8: BIBLIOGRAPHY

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APPENDICES

Appendix A. Vita 95 VMK dentine ceramic firing

1. Pre-drying at 600 degrees Celsius for six minutes
2. Increase temperature for six minutes at a rate of rise of 55 degrees Celsius per minute
3. Held at maximum temperature (930 degrees Celsius) for one minute
4. The process was held under vacuum for six minutes

Appendix B. Vita 95 VMK wash opaque (paste) ceramic firing

1. Pre-drying at 500 degrees Celsius for six minutes
2. Increase temperature for six minutes at a rate of rise of 75 degrees Celsius per minute
3. Held at maximum temperature (950 degrees Celsius) for one minute
4. The process was held under vacuum for six minutes

Appendix C. Vita 95 VMK shade designated opaque ceramic (paste) firing

1. Pre-drying at 500 degrees Celsius for six minutes
2. Increase temperature for six minutes at a rate of rise of 72 degrees Celsius per minute
3. Held at maximum temperature (930 degrees Celsius) for one minute
4. The process was held under vacuum for six minutes

Appendix D. Summary of Expt. 6B Results: Shade D4 Metal-Ceramic Samples

			Mean	Maximum	Minimum	Standard Deviation	Coefficient of variation
Original Powder (Day 1)	Tab 1						
	L		69.19	69.19	69.19	0.00	0.00%
	a		1.98	1.99	1.98	0.00	0.17%
	b		17.96	17.97	17.95	0.01	0.04%
	Tab 2						
	L		69.71	69.71	69.70	0.00	0.00%
	a		2.13	2.14	2.12	0.01	0.27%
	b		17.75	17.76	17.74	0.01	0.04%
	Tab 3						
	L		69.53	69.54	69.53	0.00	0.01%
	a		2.12	2.13	2.12	0.00	0.21%
	b		17.85	17.87	17.84	0.01	0.04%
Original Powder (Day 2)	Tab 1						
	L		69.71	69.71	69.70	0.00	0.00%
	a		2.13	2.14	2.12	0.01	0.27%
	b		17.75	17.76	17.74	0.01	0.04%
	Tab 2						
	L		69.71	69.71	69.70	0.00	0.00%
	a		2.13	2.14	2.12	0.01	0.27%
	b		17.75	17.76	17.74	0.01	0.04%
	Tab 3						
	L		69.53	69.54	69.53	0.00	0.01%
	a		2.12	2.13	2.12	0.00	0.21%
	b		17.85	17.87	17.84	0.01	0.04%
New Ceramic Powder (Day 1)	Tab 1						
	L		69.68	69.68	69.66	0.01	0.01%
	a		2.11	2.12	2.11	0.01	0.24%
	b		17.68	17.69	17.66	0.01	0.05%
	Tab 2						
	L		69.65	69.66	69.64	0.00	0.01%
	a		1.90	1.91	1.90	0.00	0.24%
	b		17.25	17.27	17.23	0.01	0.06%
	Tab 3						
	L		69.92	69.92	69.91	0.00	0.01%
	a		1.83	1.84	1.82	0.00	0.23%
	b		17.09	17.10	17.07	0.01	0.04%
New Ceramic Powder (Day 2)	Tab 1						
	L		69.64	69.65	69.63	0.01	0.01%
	a		2.22	2.23	2.22	0.01	0.23%
	b		17.74	17.76	17.72	0.01	0.04%
	Tab 2						
	L		69.50	69.51	69.50	0.00	0.01%
	a		1.88	1.89	1.87	0.01	0.27%
	b		17.10	17.11	17.08	0.01	0.04%
	Tab 3						
	L		69.88	69.89	69.88	0.01	0.01%
	a		1.79	1.80	1.78	0.01	0.28%
	b		16.93	16.95	16.92	0.01	0.05%

Appendix E. Pilot Study 1: Summary of the Mean Colour co-ordinates with Standard Deviations (SD) and Coefficient of Variations (CV)

		L*			a*			b*		
		Mean	**SD**	**CV**	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**
Group A	Tab 1	76.34	0.01	0.01%	5.44	0.01	0.11%	20.02	0.01	0.06%
	Tab 2	76.60	0.01	0.01%	5.16	0.01	0.11%	19.96	0.01	0.05%
	Tab 3	76.44	0.01	0.01%	5.34	0.01	0.10%	20.32	0.01	0.04%
	Tab 4	76.74	0.01	0.01%	5.21	0.01	0.10%	20.74	0.01	0.03%
	Tab 5	76.63	0.01	0.01%	5.19	0.01	0.12%	20.09	0.01	0.03%
	Tab 6	76.26	0.01	0.01%	5.41	0.00	0.03%	20.54	0.01	0.02%
	Tab 7	76.47	0.01	0.01%	5.21	0.00	0.08%	20.28	0.00	0.02%
	Tab 8	76.28	0.00	0.01%	5.31	0.00	0.09%	20.47	0.00	0.02%
	Tab 9	76.29	0.00	0.01%	5.47	0.01	0.11%	20.29	0.01	0.03%
	Tab 10	76.52	0.01	0.01%	5.44	0.00	0.05%	20.40	0.00	0.02%
Group B	Tab 1	74.77	0.01	0.01%	5.40	0.01	0.12%	20.93	0.01	0.05%
	Tab 2	74.53	0.01	0.01%	5.30	0.01	0.11%	20.95	0.01	0.03%
	Tab 3	74.60	0.01	0.01%	5.34	0.01	0.10%	19.97	0.02	0.08%
	Tab 4	74.22	0.01	0.01%	5.29	0.00	0.09%	20.54	0.01	0.04%
	Tab 5	74.64	0.01	0.01%	5.36	0.00	0.09%	20.93	0.01	0.04%
	Tab 6	74.86	0.01	0.02%	5.27	0.00	0.05%	20.23	0.01	0.05%
	Tab 7	74.26	0.01	0.01%	5.40	0.01	0.11%	20.44	0.01	0.04%
	Tab 8	74.21	0.01	0.02%	5.31	0.00	0.07%	20.30	0.01	0.04%
	Tab 9	74.98	0.00	0.01%	5.40	0.00	0.00%	20.55	0.01	0.04%
	Tab 10	74.29	0.00	0.00%	5.30	0.00	0.06%	20.35	0.03	0.14%

Appendix F. Pilot Study 2: Experiment 8B: Summary of the Mean Colour co-ordinates with Standard Deviations (SD) and Coefficient of Variations (CV)

		L*			a*			b*		
		Mean	**SD**	**CV**	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**
Group A	Tab 1	77.45	0.00	0.00%	4.56	0.01	0.12%	18.36	0.01	0.05%
	Tab 2	77.57	0.00	0.00%	4.61	0.01	0.15%	18.29	0.01	0.03%
	Tab 3	77.02	0.00	0.00%	4.38	0.01	0.12%	18.29	0.01	0.04%
	Tab 4	77.52	0.00	0.00%	4.33	0.01	0.12%	18.22	0.01	0.05%
	Tab 5	77.63	0.00	0.00%	4.22	0.01	0.17%	18.13	0.02	0.09%
Group B	Tab 1	71.21	0.00	0.01%	4.59	0.01	0.17%	19.19	0.01	0.06%
	Tab 2	72.34	0.01	0.01%	4.69	0.01	0.11%	18.81	0.02	0.11%
	Tab 3	71.58	0.00	0.01%	4.88	0.01	0.12%	19.58	0.01	0.04%
	Tab 4	71.44	0.03	0.04%	4.51	0.01	0.24%	18.51	0.05	0.28%
	Tab 5	71.79	0.01	0.01%	4.11	0.01	0.19%	18.89	0.01	0.07%
Group C	Tab 1	70.71	0.00	0.01%	4.40	0.00	0.11%	18.41	0.01	0.05%
	Tab 2	70.77	0.00	0.01%	4.40	0.01	0.15%	18.40	0.01	0.05%
	Tab 3	70.44	0.00	0.01%	4.37	0.01	0.16%	17.95	0.01	0.06%
	Tab 4	70.57	0.01	0.01%	4.39	0.01	0.18%	18.01	0.01	0.05%
	Tab 5	70.59	0.01	0.02%	4.43	0.01	0.16%	17.89	0.01	0.05%
Group D	Tab 1	74.97	0.00	0.00%	3.86	0.01	0.13%	15.91	0.01	0.06%
	Tab 2	74.89	0.00	0.00%	3.89	0.01	0.13%	15.97	0.01	0.07%
	Tab 3	74.91	0.00	0.00%	3.96	0.01	0.17%	15.28	0.01	0.05%
	Tab 4	74.34	0.00	0.00%	3.83	0.01	0.15%	15.54	0.01	0.05%
	Tab 5	74.92	0.03	0.04%	3.60	0.01	0.21%	15.36	0.01	0.07%

Appendix G. Experiment 8, Shade B1: Group A Samples (Uncondensed)

			Mean	Maximum	Minimum	Standard Deviation	Coefficient of variation
Shade B1 - Uncondensed							
	Tab 1						
	L		76.34	76.35	76.34	0.00	0.00%
	a		0.68	0.70	0.66	0.01	1.14%
	b		12.44	12.47	12.41	0.01	0.09%
	Tab 2						
	L		76.74	76.75	76.73	0.00	0.00%
	a		0.49	0.51	0.48	0.01	1.37%
	b		12.14	12.15	12.12	0.01	0.09%
	Tab 3						
	L		76.61	76.61	76.60	0.00	0.01%
	a		0.53	0.54	0.52	0.01	1.29%
	b		12.15	12.17	12.12	0.01	0.09%
	Tab 4						
	L		76.86	76.86	76.85	0.00	0.00%
	a		0.79	0.80	0.78	0.01	0.95%
	b		12.12	12.14	12.11	0.01	0.08%
	Tab 5						
	L		76.58	76.59	76.57	0.01	0.01%
	a		0.89	0.90	0.88	0.01	0.69%
	b		12.26	12.29	12.24	0.01	0.10%
	Tab 6						
	L		76.15	76.16	76.14	0.01	0.01%
	a		1.08	1.09	1.07	0.01	0.51%
	b		12.91	12.94	12.89	0.01	0.09%
	Tab 7						
	L		76.36	76.37	76.35	0.00	0.01%
	a		1.14	1.15	1.13	0.01	0.56%
	b		13.05	13.07	13.02	0.01	0.09%
	Tab 8						
	L		76.50	76.50	76.49	0.00	0.01%
	a		0.54	0.55	0.53	0.01	1.23%
	b		12.14	12.16	12.12	0.01	0.07%
	Tab 9						
	L		76.07	76.08	76.07	0.00	0.01%
	a		0.66	0.67	0.65	0.01	0.95%
	b		12.27	12.28	12.25	0.01	0.07%
	Tab 10						
	L		76.51	76.52	76.51	0.00	0.00%
	a		0.89	0.90	0.88	0.01	0.75%
	b		12.28	12.31	12.27	0.01	0.08%

Appendix H. Experiment 8, Shade B1: Group B Samples (Hand Vibration)

			Mean	Standard Deviation	Coefficient of variation
Shade B1 - Vibrate					
	Tab 1				
	L		75.33	0.00	0.00%
	a		0.65	0.01	1.02%
	b		11.35	0.01	0.09%
	Tab 2				
	L		75.42	0.00	0.01%
	a		0.59	0.01	0.90%
	b		11.25	0.01	0.08%
	Tab 3				
	L		75.91	0.00	0.01%
	a		0.38	0.01	1.62%
	b		11.15	0.01	0.09%
	Tab 4				
	L		75.25	0.00	0.00%
	a		0.40	0.01	1.73%
	b		10.92	0.01	0.09%
	Tab 5				
	L		74.19	0.00	0.00%
	a		0.57	0.01	1.35%
	b		10.99	0.01	0.08%
	Tab 6				
	L		73.95	0.00	0.01%
	a		0.61	0.01	0.92%
	b		10.91	0.01	0.08%
	Tab 7				
	L		75.02	0.01	0.01%
	a		0.66	0.01	0.94%
	b		11.94	0.01	0.08%
	Tab 8				
	L		75.23	0.01	0.01%
	a		0.68	0.01	0.99%
	b		11.81	0.01	0.08%
	Tab 9				
	L		75.71	0.00	0.00%
	a		0.10	0.01	6.88%
	b		10.77	0.01	0.08%
	Tab 10				
	L		75.44	0.00	0.00%
	a		0.27	0.01	2.17%
	b		11.08	0.01	0.06%

Appendix I. Experiment 8, Shade B1: Group C Samples (Ultrasonic)

			Mean	Maximum	Minimum	Standard Deviation	Coefficient of variation
Shade B1 - Ultrasonic							
	Tab 1						
	L		75.18	75.19	75.18	0.00	0.00%
	a		0.10	0.12	0.08	0.01	7.83%
	b		10.40	10.42	10.37	0.01	0.10%
	Tab 2						
	L		75.03	75.04	75.02	0.00	0.00%
	a		0.12	0.13	0.10	0.01	5.87%
	b		10.32	10.34	10.31	0.01	0.09%
	Tab 3						
	L		75.97	75.98	75.97	0.00	0.00%
	a		0.07	0.08	0.06	0.00	7.12%
	b		10.51	10.53	10.49	0.01	0.09%
	Tab 4						
	L		75.97	75.97	75.97	0.00	0.00%
	a		0.07	0.08	0.06	0.01	7.94%
	b		10.50	10.52	10.47	0.01	0.09%
	Tab 5						
	L		74.90	74.90	74.89	0.00	0.00%
	a		0.34	0.35	0.33	0.01	1.63%
	b		10.79	10.81	10.77	0.01	0.09%
	Tab 6						
	L		74.97	74.97	74.96	0.00	0.00%
	a		0.24	0.26	0.23	0.01	2.49%
	b		10.55	10.56	10.53	0.01	0.08%
	Tab 7						
	L		74.93	74.94	74.93	0.00	0.01%
	a		0.37	0.38	0.36	0.01	1.73%
	b		10.89	10.91	10.86	0.01	0.11%
	Tab 8						
	L		75.09	75.09	75.09	0.00	0.00%
	a		0.24	0.26	0.23	0.01	2.40%
	b		10.39	10.41	10.37	0.01	0.09%
	Tab 9						
	L		75.01	75.02	75.01	0.00	0.01%
	a		0.22	0.23	0.21	0.01	2.54%
	b		10.70	10.71	10.68	0.01	0.07%
	Tab 10						
	L		75.53	75.54	75.53	0.00	0.00%
	a		0.31	0.32	0.30	0.01	2.40%
	b		11.08	11.10	11.07	0.01	0.07%

Appendix J. Experiment 8, Shade B1: Group D Samples (Addition of Powder)

			Mean	Maximum	Minimum	Standard Deviation	Coefficient of variation
Shade B1 - Powder							
	Tab 1						
	L		79.49	79.50	79.49	0.00	0.00%
	a		0.60	0.61	0.59	0.01	1.10%
	b		11.67	11.69	11.65	0.01	0.09%
	Tab 2						
	L		79.86	79.86	79.85	0.00	0.00%
	a		0.66	0.67	0.65	0.01	0.92%
	b		11.62	11.64	11.60	0.01	0.08%
	Tab 3						
	L		81.12	81.12	81.11	0.00	0.00%
	a		0.60	0.61	0.60	0.00	0.79%
	b		11.38	11.40	11.35	0.01	0.11%
	Tab 4						
	L		80.83	80.83	80.82	0.00	0.00%
	a		0.61	0.63	0.60	0.01	1.01%
	b		11.70	11.73	11.69	0.01	0.09%
	Tab 5						
	L		79.81	79.82	79.81	0.00	0.01%
	a		0.43	0.45	0.42	0.01	1.42%
	b		11.69	11.72	11.68	0.01	0.08%
	Tab 6						
	L		80.33	80.33	80.31	0.01	0.01%
	a		0.28	0.29	0.27	0.01	2.20%
	b		11.12	11.13	11.11	0.01	0.05%
	Tab 7						
	L		79.16	79.16	79.15	0.00	0.01%
	a		0.64	0.66	0.63	0.01	1.05%
	b		11.53	11.55	11.51	0.01	0.10%
	Tab 8						
	L		78.92	78.93	78.92	0.00	0.01%
	a		0.58	0.58	0.57	0.01	0.88%
	b		11.31	11.34	11.30	0.01	0.09%
	Tab 9						
	L		81.13	81.14	81.12	0.00	0.00%
	a		0.52	0.53	0.50	0.01	1.26%
	b		11.16	11.18	11.14	0.01	0.09%
	Tab 10						
	L		81.20	81.20	81.19	0.00	0.00%
	a		0.56	0.56	0.54	0.01	1.13%
	b		11.21	11.23	11.20	0.01	0.08%

Appendix K. Experiment 8, Shade A3: Group A Samples (Uncondensed)

			Mean	Maximum	Minimum	Standard Deviation	Coefficient of variation
Shade A3 - Uncondensed							
	Tab 1						
	L		76.52	76.53	76.52	0.00	0.01%
	a		4.79	4.80	4.78	0.01	0.14%
	b		19.56	19.58	19.55	0.01	0.03%
	Tab 2						
	L		76.16	76.16	76.16	0.00	0.00%
	a		5.20	5.22	5.19	0.01	0.15%
	b		19.82	19.83	19.79	0.01	0.05%
	Tab 3						
	L		76.38	76.39	76.37	0.00	0.00%
	a		5.13	5.15	5.12	0.01	0.12%
	b		19.69	19.70	19.67	0.01	0.04%
	Tab 4						
	L		76.83	76.83	76.82	0.01	0.01%
	a		4.45	4.46	4.43	0.01	0.14%
	b		19.46	19.48	19.44	0.01	0.05%
	Tab 5						
	L		76.84	76.84	76.83	0.01	0.01%
	a		4.55	4.57	4.54	0.01	0.14%
	b		18.12	18.14	18.10	0.01	0.06%
	Tab 6						
	L		77.40	77.40	77.39	0.00	0.00%
	a		5.18	5.19	5.17	0.01	0.12%
	b		18.14	18.16	18.13	0.01	0.04%
	Tab 7						
	L		77.60	77.60	77.59	0.01	0.01%
	a		5.20	5.21	5.18	0.01	0.13%
	b		18.18	18.20	18.16	0.01	0.05%
	Tab 8						
	L		77.81	77.82	77.81	0.01	0.01%
	a		4.93	4.94	4.92	0.01	0.14%
	b		18.08	18.10	18.06	0.01	0.06%
	Tab 9						
	L		77.96	77.96	77.95	0.00	0.00%
	a		4.75	4.76	4.74	0.01	0.12%
	b		19.91	19.93	19.90	0.01	0.04%
	Tab 10						
	L		76.98	76.99	76.98	0.00	0.00%
	a		5.10	5.11	5.09	0.01	0.11%
	b		19.61	19.63	19.59	0.01	0.05%

Appendix L. Experiment 8, Shade A3: Group B Samples (Hand Vibration)

			Mean	Maximum	Minimum	Standard Deviation	Coefficient of variation
Shade A3 - Vibrate							
	Tab 1						
	L		73.86	73.86	73.85	0.01	0.01%
	a		4.67	4.68	4.66	0.00	0.09%
	b		20.10	20.12	20.08	0.01	0.05%
	Tab 2						
	L		73.72	73.72	73.71	0.00	0.01%
	a		4.63	4.64	4.62	0.01	0.13%
	b		20.19	20.21	20.18	0.01	0.04%
	Tab 3						
	L		73.88	73.88	73.87	0.01	0.01%
	a		4.99	5.00	4.98	0.01	0.12%
	b		20.02	20.03	19.99	0.01	0.06%
	Tab 4						
	L		73.61	73.61	73.60	0.00	0.01%
	a		4.94	4.95	4.92	0.01	0.13%
	b		19.96	19.97	19.94	0.01	0.04%
	Tab 5						
	L		73.48	73.48	73.48	0.00	0.00%
	a		5.26	5.27	5.25	0.01	0.10%
	b		20.31	20.33	20.29	0.01	0.05%
	Tab 6						
	L		73.66	73.67	73.66	0.00	0.00%
	a		5.24	5.25	5.23	0.00	0.08%
	b		20.56	20.57	20.54	0.01	0.04%
	Tab 7						
	L		73.89	73.89	73.89	0.00	0.00%
	a		5.14	5.15	5.13	0.01	0.12%
	b		20.31	20.33	20.28	0.01	0.06%
	Tab 8						
	L		73.09	73.10	73.09	0.00	0.01%
	a		5.12	5.14	5.11	0.01	0.14%
	b		20.32	20.34	20.29	0.01	0.05%
	Tab 9						
	L		73.64	73.65	73.64	0.00	0.00%
	a		5.12	5.13	5.11	0.00	0.08%
	b		20.46	20.48	20.45	0.01	0.04%
	Tab 10						
	L		73.82	73.82	73.81	0.00	0.01%
	a		5.19	5.20	5.18	0.01	0.12%
	b		20.50	20.52	20.48	0.01	0.05%

Appendix M. Experiment 8, Shade A3: Group C Samples (Ultrasonic)

			Mean	Maximum	Minimum	Standard Deviation	Coefficient of variation
Shade A3 - Ultrasonic							
	Tab 1						
	L		72.91	72.91	72.90	0.00	0.01%
	a		4.85	4.87	4.84	0.01	0.17%
	b		18.15	18.18	18.14	0.01	0.06%
	Tab 2						
	L		72.97	72.97	72.96	0.01	0.01%
	a		4.85	4.86	4.84	0.01	0.11%
	b		18.56	18.57	18.54	0.01	0.04%
	Tab 3						
	L		73.07	73.08	73.07	0.00	0.00%
	a		4.71	4.72	4.70	0.01	0.13%
	b		17.81	17.82	17.79	0.01	0.05%
	Tab 4						
	L		72.45	72.45	72.44	0.00	0.00%
	a		4.69	4.70	4.68	0.01	0.12%
	b		17.97	17.98	17.95	0.01	0.05%
	Tab 5						
	L		72.72	72.72	72.71	0.00	0.01%
	a		4.61	4.62	4.60	0.01	0.12%
	b		17.45	17.47	17.43	0.01	0.06%
	Tab 6						
	L		72.18	72.18	72.17	0.00	0.01%
	a		4.51	4.52	4.50	0.01	0.15%
	b		17.39	17.41	17.38	0.01	0.05%
	Tab 7						
	L		72.59	72.59	72.59	0.00	0.00%
	a		4.59	4.60	4.58	0.01	0.11%
	b		17.89	17.90	17.87	0.01	0.05%
	Tab 8						
	L		72.84	72.85	72.84	0.01	0.01%
	a		4.51	4.52	4.50	0.01	0.16%
	b		17.65	17.66	17.63	0.01	0.05%
	Tab 9						
	L		72.17	72.17	72.16	0.00	0.01%
	a		4.68	4.69	4.67	0.01	0.13%
	b		18.75	18.77	18.73	0.01	0.06%
	Tab 10						
	L		72.35	72.35	72.34	0.00	0.01%
	a		4.53	4.54	4.52	0.01	0.12%
	b		18.33	18.35	18.31	0.01	0.05%

Appendix N. Experiment 8, Shade A3: Group D Samples (Addition of Powder)

			Mean	Maximum	Minimum	Standard Deviation	Coefficient of variation
Shade A3 - Powder							
	Tab 1						
	L		73.03	73.03	73.03	0.00	0.00%
	a		5.25	5.25	5.23	0.01	0.11%
	b		20.11	20.13	20.09	0.01	0.05%
	Tab 2						
	L		73.23	73.24	73.23	0.01	0.01%
	a		5.09	5.10	5.08	0.01	0.10%
	b		19.92	19.94	19.90	0.01	0.04%
	Tab 3						
	L		72.68	72.69	72.67	0.00	0.01%
	a		4.89	4.90	4.88	0.01	0.13%
	b		18.88	18.90	18.86	0.01	0.05%
	Tab 4						
	L		72.33	72.33	72.32	0.00	0.00%
	a		4.88	4.90	4.87	0.01	0.13%
	b		18.78	18.80	18.77	0.01	0.04%
	Tab 5						
	L		73.27	73.27	73.27	0.00	0.00%
	a		4.98	4.99	4.97	0.01	0.13%
	b		18.91	18.93	18.89	0.01	0.04%
	Tab 6						
	L		73.14	73.15	73.14	0.01	0.01%
	a		4.93	4.94	4.92	0.01	0.13%
	b		18.91	18.92	18.89	0.01	0.04%
	Tab 7						
	L		72.61	72.61	72.60	0.00	0.01%
	a		5.32	5.33	5.31	0.01	0.12%
	b		19.86	19.88	19.85	0.01	0.05%
	Tab 8						
	L		72.85	72.85	72.84	0.00	0.00%
	a		5.28	5.29	5.27	0.01	0.12%
	b		19.94	19.96	19.93	0.01	0.05%
	Tab 9						
	L		72.54	72.55	72.54	0.00	0.00%
	a		4.91	4.91	4.90	0.00	0.10%
	b		19.96	19.98	19.94	0.01	0.05%
	Tab 10						
	L		72.61	72.62	72.61	0.00	0.01%
	a		4.90	4.92	4.89	0.01	0.16%
	b		20.01	20.02	19.99	0.01	0.04%

Appendix O. Experiment 8, Shade D4: Group A Samples (Uncondensed)

			Mean	Maximum	Minimum	Standard Deviation	Coefficient of variation
Shade D4 - Uncondensed							
	Tab 1						
	L		68.79	68.79	68.79	0.00	0.00%
	a		4.24	4.25	4.23	0.01	0.12%
	b		16.55	16.58	16.51	0.02	0.09%
	Tab 2						
	L		67.08	67.08	67.07	0.00	0.01%
	a		4.39	4.41	4.38	0.01	0.15%
	b		17.19	17.21	17.17	0.01	0.06%
	Tab 3						
	L		66.38	66.39	66.37	0.01	0.01%
	a		4.42	4.43	4.41	0.01	0.13%
	b		17.34	17.36	17.32	0.01	0.06%
	Tab 4						
	L		66.97	66.97	66.96	0.00	0.01%
	a		4.57	4.58	4.55	0.01	0.17%
	b		18.28	18.30	18.25	0.01	0.08%
	Tab 5						
	L		67.00	67.01	67.00	0.00	0.01%
	a		4.37	4.38	4.36	0.00	0.11%
	b		17.26	17.27	17.23	0.01	0.06%
	Tab 6						
	L		66.51	66.51	66.50	0.00	0.00%
	a		4.40	4.41	4.39	0.01	0.14%
	b		17.29	17.33	17.28	0.01	0.06%
	Tab 7						
	L		66.99	66.99	66.98	0.00	0.01%
	a		4.85	4.86	4.84	0.01	0.13%
	b		18.26	18.28	18.24	0.01	0.07%
	Tab 8						
	L		69.04	69.05	69.04	0.00	0.00%
	a		4.15	4.16	4.14	0.01	0.16%
	b		16.47	16.49	16.45	0.01	0.07%
	Tab 9						
	L		69.10	69.10	69.09	0.00	0.01%
	a		4.16	4.17	4.14	0.01	0.17%
	b		16.40	16.42	16.38	0.01	0.07%
	Tab 10						
	L		67.04	67.05	67.04	0.00	0.01%
	a		4.43	4.44	4.41	0.01	0.14%
	b		17.25	17.27	17.23	0.01	0.07%

Appendix P. Experiment 8, Shade D4: Group B Samples (Hand Vibration)

			Mean	Maximum	Minimum	Standard Deviation	Coefficient of variation
Shade D4 - Vibrate							
	Tab 1						
	L		66.69	66.70	66.69	0.00	0.01%
	a		4.65	4.67	4.64	0.01	0.15%
	b		17.68	17.71	17.65	0.01	0.08%
	Tab 2						
	L		65.71	65.71	65.70	0.01	0.01%
	a		4.47	4.48	4.45	0.01	0.16%
	b		17.81	17.84	17.78	0.01	0.07%
	Tab 3						
	L		65.86	65.87	65.85	0.01	0.01%
	a		4.50	4.51	4.49	0.01	0.13%
	b		17.87	17.91	17.84	0.01	0.08%
	Tab 4						
	L		66.29	66.30	66.29	0.00	0.01%
	a		4.47	4.48	4.46	0.01	0.13%
	b		17.04	17.06	17.02	0.01	0.07%
	Tab 5						
	L		66.30	66.31	66.29	0.01	0.01%
	a		4.46	4.47	4.45	0.01	0.14%
	b		16.99	17.01	16.97	0.01	0.06%
	Tab 6						
	L		65.81	65.82	65.80	0.01	0.01%
	a		4.40	4.41	4.38	0.01	0.13%
	b		17.19	17.21	17.17	0.01	0.06%
	Tab 7						
	L		65.60	65.60	65.59	0.00	0.01%
	a		4.39	4.40	4.38	0.01	0.13%
	b		17.35	17.37	17.33	0.01	0.06%
	Tab 8						
	L		65.62	65.63	65.62	0.00	0.01%
	a		4.46	4.47	4.44	0.01	0.16%
	b		17.81	17.83	17.79	0.01	0.06%
	Tab 9						
	L		66.59	66.60	66.58	0.00	0.01%
	a		4.65	4.66	4.64	0.01	0.13%
	b		17.69	17.71	17.66	0.01	0.07%
	Tab 10						
	L		65.13	65.14	65.13	0.01	0.01%
	a		4.59	4.61	4.58	0.01	0.15%
	b		16.90	16.93	16.89	0.01	0.05%

Appendix Q. Experiment 8, Shade D4: Group C Samples (Ultrasonic)

			Mean	Maximum	Minimum	Standard Deviation	Coefficient of variation
Shade D4 - Ultrasonic							
	Tab 1						
	L		60.37	60.38	60.37	0.00	0.01%
	a		4.34	4.35	4.33	0.01	0.18%
	b		17.24	17.27	17.22	0.02	0.09%
	Tab 2						
	L		60.71	60.72	60.71	0.01	0.01%
	a		4.25	4.26	4.24	0.01	0.15%
	b		16.89	16.91	16.86	0.01	0.07%
	Tab 3						
	L		60.79	60.80	60.79	0.01	0.01%
	a		4.74	4.76	4.73	0.01	0.15%
	b		18.08	18.11	18.06	0.01	0.06%
	Tab 4						
	L		60.75	60.75	60.74	0.00	0.01%
	a		4.74	4.75	4.72	0.01	0.14%
	b		18.06	18.09	18.03	0.01	0.07%
	Tab 5						
	L		60.14	60.15	60.14	0.00	0.01%
	a		4.43	4.44	4.42	0.01	0.15%
	b		16.79	16.82	16.77	0.01	0.07%
	Tab 6						
	L		60.33	60.33	60.32	0.00	0.01%
	a		4.41	4.42	4.40	0.01	0.12%
	b		16.65	16.67	16.64	0.01	0.05%
	Tab 7						
	L		61.40	61.41	61.39	0.00	0.00%
	a		4.49	4.50	4.48	0.01	0.14%
	b		18.11	18.13	18.10	0.01	0.05%
	Tab 8						
	L		60.82	60.82	60.81	0.01	0.01%
	a		4.59	4.60	4.58	0.01	0.15%
	b		17.46	17.48	17.43	0.01	0.07%
	Tab 9						
	L		60.00	60.01	59.99	0.00	0.01%
	a		4.68	4.69	4.67	0.01	0.12%
	b		17.21	17.23	17.18	0.01	0.06%
	Tab 10						
	L		59.81	59.81	59.80	0.00	0.01%
	a		4.70	4.71	4.69	0.01	0.14%
	b		17.29	17.31	17.27	0.01	0.06%

Appendix R. Experiment 8, Shade D4: Group D Samples (Addition of Powder)

			Mean	Maximum	Minimum	Standard Deviation	Coefficient of variation
Shade D4 - Powder							
	Tab 1						
	L		68.10	68.11	68.10	0.01	0.01%
	a		4.52	4.53	4.51	0.01	0.13%
	b		17.79	17.80	17.77	0.01	0.05%
	Tab 2						
	L		67.87	67.88	67.87	0.00	0.01%
	a		4.56	4.58	4.55	0.01	0.13%
	b		17.92	17.94	17.91	0.01	0.04%
	Tab 3						
	L		68.18	68.18	68.17	0.00	0.00%
	a		4.44	4.45	4.43	0.01	0.15%
	b		17.73	17.75	17.70	0.01	0.06%
	Tab 4						
	L		68.61	68.61	68.61	0.00	0.00%
	a		4.40	4.41	4.39	0.01	0.15%
	b		17.53	17.54	17.51	0.01	0.05%
	Tab 5						
	L		68.48	68.49	68.47	0.01	0.01%
	a		4.55	4.56	4.55	0.00	0.11%
	b		17.22	17.24	17.21	0.01	0.05%
	Tab 6						
	L		68.41	68.41	68.40	0.01	0.01%
	a		4.52	4.52	4.51	0.00	0.11%
	b		16.98	17.00	16.97	0.01	0.05%
	Tab 7						
	L		67.74	67.75	67.74	0.00	0.01%
	a		4.34	4.35	4.33	0.01	0.14%
	b		17.02	17.04	17.00	0.01	0.06%
	Tab 8						
	L		67.94	67.94	67.93	0.00	0.01%
	a		4.31	4.32	4.31	0.00	0.12%
	b		17.02	17.03	16.99	0.01	0.07%
	Tab 9						
	L		68.91	68.92	68.91	0.00	0.01%
	a		4.09	4.10	4.07	0.01	0.16%
	b		16.75	16.77	16.73	0.01	0.07%
	Tab 10						
	L		68.95	68.96	68.95	0.00	0.01%
	a		4.20	4.21	4.19	0.01	0.15%
	b		16.85	16.88	16.83	0.01	0.06%

Appendix S. Experiment 2A (Normal Tabs under Dental Surgery Lighting): Colour co-ordinates, coefficient of variations and the colour difference between the mean and the remaining measurements

		Shade B1				Shade A3				Shade C4			
				dEoo				dEoo					dEoo
	101.49	0.29	21.22		78.78	0.40	16.22		0.70	65.84	0.51	10.72	
	104.36	0.28	21.93	0.17	79.53	0.40	16.21		0.18	65.67	0.51	10.81	0.20
	104.03	0.28	21.35	0.18	79.94	0.40	16.14		0.16	65.18	0.51	10.95	0.29
	103.61	0.28	21.89	0.31	79.55	0.40	16.34		0.16	64.78	0.52	10.67	0.55
	102.54	0.28	21.59	0.89	79.91	0.40	16.28		0.10	65.76	0.51	10.85	0.28
	103.20	0.28	21.85	0.53	79.39	0.40	16.26		0.27	65.92	0.52	10.74	0.39
	104.16	0.28	21.55	0.07	80.40	0.39	16.18		0.44	65.56	0.51	10.72	0.10
	104.18	0.28	21.52	0.09	79.39	0.40	16.39		0.27	65.61	0.52	10.67	0.13
	104.69	0.28	21.32	0.36	80.50	0.40	16.32		0.50	65.38	0.51	10.75	0.08
	104.78	0.28	21.63	0.35	80.01	0.40	16.32		0.16	65.67	0.52	10.61	0.18
	104.07	0.28	21.37	0.16	80.38	0.40	16.23		0.42	65.51	0.52	10.47	0.14
	103.92	0.28	21.51	0.15	79.31	0.41	16.30		0.32	65.71	0.51	10.79	0.23
	104.68	0.28	21.47	0.32	80.32	0.40	16.50		0.39	64.72	0.52	10.73	0.60
	105.03	0.28	21.54	0.50	79.86	0.40	16.19		0.10	65.79	0.51	10.85	0.30
	104.51	0.28	21.65	0.21	79.15	0.40	16.54		0.45	65.77	0.51	10.78	0.27
	104.86	0.28	21.78	0.40	79.33	0.39	16.65		0.36	64.93	0.52	10.63	0.43
	103.13	0.28	22.12	0.60	79.91	0.40	16.37		0.10	65.03	0.52	10.67	0.34
	104.21	0.28	21.69	0.04	80.18	0.40	16.50		0.30	65.24	0.51	10.91	0.24
	104.51	0.28	21.59	0.21	79.36	0.39	16.52		0.31	65.42	0.52	10.82	0.10
	105.64	0.27	21.68	0.82	79.42	0.40	16.11		0.28	64.75	0.52	10.68	0.58
	105.04	0.28	21.52	0.50	79.97	0.40	16.35		0.14	65.36	0.51	10.59	0.09
	103.64	0.28	21.84	0.29	79.64	0.40	16.21		0.12	65.89	0.52	10.52	0.37
	102.73	0.28	21.96	0.80	80.08	0.40	16.26		0.22	65.87	0.51	10.53	0.36
	105.14	0.28	21.89	0.56	80.19	0.40	16.30		0.29	65.11	0.51	10.47	0.31
	102.46	0.28	22.11	0.96	79.93	0.40	16.29		0.11	65.43	0.52	10.56	0.08
	103.95	0.28	21.95	0.17	79.60	0.40	16.51		0.16	65.85	0.51	10.61	0.33
	105.83	0.28	21.28	0.95	79.34	0.40	16.40		0.30	65.44	0.52	10.54	0.09
	103.24	0.28	21.96	0.52	80.05	0.40	16.34		0.19	65.41	0.51	10.75	0.07
	104.56	0.28	21.78	0.24	79.71	0.41	16.54		0.13	65.76	0.51	10.61	0.26
	102.11	0.28	21.55	1.13	79.71	0.40	16.23		0.08	65.87	0.52	10.41	0.39
	105.37	0.27	21.64	0.68	79.17	0.40	16.30		0.42	65.07	0.52	10.53	0.33
Mean	104.14	0.28	21.68	0.44	79.77	0.40	16.34		0.25	65.45	0.52	10.67	0.27
Median				0.36					0.25				0.28
Maximum	105.83	0.28	22.12	1.13	80.50	0.41	16.65		0.50	65.92	0.52	10.95	0.60
Minimum	102.11	0.27	21.28	0.04	79.15	0.39	16.11		0.08	64.72	0.51	10.41	0.07
Standard Deviation	1.05	0.00	0.24	0.30	0.42	0.00	0.13		0.15	0.37	0.01	0.14	0.15
Coefficient of variation	1.01%	1.13%	1.11%		0.53%	1.02%	0.81%			0.56%	0.99%	1.27%	

Appendix T. Experiment 3B: Shade Selections of Proprietary Shade Guide Tabs

Shade B1: normal tab				Shade A3: normal tab				Shade C4:normal tab				Shade B1: ground tab				Shade A3: ground tab				Shade C4:ground tab		
	Day 1	Day 2			Day 1	Day 2			Day 1	Day 2			Day 1	Day 2			Day 1	Day 2			Day 1	Day 2
1	A1	A1		1	A2.5	A2.5		1	C3.5	C3.5		1	A1.25	A1.25		1	B2.5	B2.5		1	A4	A4
2	A1	A1		2	A2.5	A2.5		2	C3.5	C3.5		2	A1.25	A1.25		2	B2.5	B2.5		2	A4	A4
3	A1	A1		3	A2.5	A2.5		3	C3.5	C3.5		3	A1.25	A1.25		3	B2.5	B2.5		3	A4	A4
4	A1	A1		4	A2.5	A2.5		4	C3.5	C3.5		4	A1.25	A1.25		4	B2.5	B2.5		4	A4	A4
5	A1	A1		5	A2.5	A2.5		5	C3.5	C3.5		5	A1.25	A1.25		5	B2.5	B2.5		5	A4	A4
6	A1	A1		6	A2.5	A2.5		6	C3.5	C3.5		6	A1.25	A1.25		6	B2.5	B2.5		6	A4	A4
7	A1	A1		7	A2.5	A2.5		7	C3.5	C3.5		7	A1.25	A1.25		7	B2.5	B2.5		7	A4	A4
8	A1	A1		8	A2.5	A2.5		8	C3.5	C3.5		8	A1.25	A1		8	B2.5	B2.5		8	A4	A4
9	A1	A1		9	A2.5	A2.5		9	C3.5	C3.5		9	A1.25	A1.25		9	B2.5	B2.5		9	A4	A4
10	A1	A1		10	A2.5	A2.5		10	C3.5	C3.5		10	A1.25	A1.25		10	B2.5	B2.5		10	A4	A4
11	A1	A1		11	A2.5	A2.5		11	C3.5	C3.5		11	A1.25	A1.25		11	B2.5	B2.5		11	A4	A4
12	A1	A1		12	A2.5	A2.5		12	C3.5	C3.5		12	A1.25	A1.25		12	B2.5	B2.5		12	A4	A4
13	A1	A1		13	A2.5	A2.5		13	C3.5	C3.5		13	A1.25	A1.25		13	B2.5	B2.5		13	A4	A4
14	A1	A1		14	A2.5	A2.5		14	C3.5	C3.5		14	A1.25	A1.25		14	B2.5	B2.5		14	A4	A4
15	A1	A1		15	A2.5	A2.5		15	C3.5	C3.5		15	A1.25	A1.25		15	B2.5	B2.5		15	A4	A4
16	A1	A1		16	A2.5	A2.5		16	C3.5	C3.5		16	A1.25	A1.25		16	B2.5	B2.5		16	A4	A4
17	A1	A1		17	A2.5	A2.5		17	C3.5	C3.5		17	A1.25	A1.25		17	B2.5	B2.5		17	A4	A4
18	A1	A1.5		18	A2.5	A2.5		18	C3.5	C3.5		18	A1.25	A1.25		18	B2.5	B2.5		18	A4	A4
19	A1	A1		19	A2.5	A2.5		19	C3.5	C3.5		19	A1.25	A1.25		19	B2.5	B2.5		19	A4	A4
20	A1	A1		20	A2.5	A2.5		20	C3.5	C3.5		20	A1.25	A1.25		20	B2.5	B2.5		20	A4	A4
21	A1	A1		21	A2.5	A2.5		21	C3.5	C3.5		21	A1.25	A1.25		21	B2.5	B2.5		21	A4	A4
22	A1	A1		22	A2.5	A2.5		22	C3.5	C3.5		22	A1.25	A1.25		22	B2.5	B2.5		22	A4	A4
23	A1	A1		23	A2.5	A2.5		23	C3.5	C3.5		23	A1.25	A1.25		23	B2.5	B2.5		23	A4	A4
24	A1	A1		24	A2.5	A2.5		24	C3.5	C3.5		24	A1.25	A1.25		24	B2.5	B2.5		24	A4	A4
25	A1	A1		25	A2.5	A2.5		25	C3.5	C3.5		25	A1.25	A1.25		25	B2.5	B2.5		25	A4	A4
26	A1	A1		26	A2.5	A2.5		26	C3.5	C3.5		26	A1.25	A1.25		26	B2.5	B2.5		26	A4	A4
27	A1	A1		27	A2.5	A2.5		27	C3.5	C3.5		27	A1.25	A1.25		27	B2.5	B2.5		27	A4	A4
28	A1	A1		28	A2.5	A2.5		28	C3.5	C3.5		28	A1.25	A1.25		28	B2.5	B2.5		28	A4	A4
29	A1	A1		29	A2.5	A2.5		29	C3.5	C3.5		29	A1.25	A1.25		29	B2.5	B2.5		29	A4	A4
30	A1	A1		30	A2.5	A2.5		30	C3.5	C3.5		30	A1.25	A1.25		30	B2.5	B2.5		30	A4	A4
31	A1	A1		31	A2.5	A2.5		31	C3.5	C3.5		31	A1.25	A1.25		31	B2.5	B2.5		31	A4	A4